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SCIENTIFIC AMERICAN

SUMMER 2015

THE SCIENCE OF FOOD

INSIDE

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The Truth about GMOs

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INTRODUCTION

A New View of Food

For most of human history, life revolved around food. Hunting, growing and preparing it left little time for anything else. Industrialization of the production process changed all that and made it easy—arguably too easy—to overlook the intimate connection that food has to the health of our body and the health of our planet. But today people are increasingly mindful of that connection, thanks in part to new insights and options from science.

Researchers, for example, have begun to untangle the complex web of factors that make some foods delicious (*page 4*). Experts who have devoted their careers to some of our most treasured foods can now explain the intricacies of coffee (*page 10*), champagne (*page 16*) and truffles (*page 22*). Historians have pieced together the origins of our modern diet (*page 64*) and traced the millennia-long evolution of processed food (*page 78*) and the shifting attitudes toward alcohol (*page 72*).

Now much of the discussion about food involves angst and trade-offs. Many agricultural products—not to mention farmers' livelihoods—are threatened by climate change and disease. On page 28, two top scientists at Mars, Inc., the famed candy-bar maker, describe serious threats to the future of one of our favorites—chocolate, a sweet treat that some find addictive. The notion of addiction may be more than mere metaphor. As neuroscientist Paul J. Kenny points out on page 46, overconsumption of sugary, high-fat foods such as chocolate may actually alter brain chemistry in ways similar to the effects of addictive drugs. In "Eating Made Simple" (*page 38*), nutrition expert Marion Nestle notes that the rich world is awash in such foods, which are implicated in elevated rates of obesity. Changing that environment of temptation can be part of the solution, she argues. Behavioral strategies for weight loss also show promise (*page 52*).

The globalization of agriculture and food distribution has boosted yields and prevented famines—and filled our winter salads with produce grown all over the world (*page 112*). Yet the insatiable appetite of humanity is also harming the environment in myriad ways. "Can We Feed the World and Sustain the Planet?" asks Jonathan A. Foley on page 84. An authority on sustainability, Foley proposes a plan to end malnutrition worldwide while preserving rain forests and stabilizing the climate. For that to happen, we will need to lessen the steep environmental toll exacted by beef production, which is rising rapidly (*page 108*). Informed eaters must decide for themselves whether GMO foods are acceptable (*pages 90 and 102*). How about lab-grown meat (*page 96*)? Or, as chef Bun Lai advocates on page 34, meals made from invasive species? You may not agree with all the ideas in this issue. But they are indeed food for thought.

W. Wayt Gibbs
Issue Editor
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SCIENTIFIC AMERICAN

Volume 24, No. 2, Summer 2015

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Scientific American Special (ISSN 1936-1513), Volume 24, Number 2, Summer 2015, published by Scientific American, a division of Nature America, Inc., 75 Varick Street, 9th Floor, New York, NY 10013-1917. Canadian BN No. 127387652RT; TVQ1218059275 TQ0001. To purchase additional quantities: U.S., $13.95 each; elsewhere, $17.95 each. Send payment to Scientific American Back Issues, 75 Varick Street, 9th Floor, New York, NY 10013-1917. **Inquiries: fax 212-355-0408 or telephone 212-451-8415. Printed in U.S.A.**

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Articles in this special issue are updated from previous issues of *Scientific American*.

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COGNITIVE SCIENCE

WHAT MAKES FOOD TASTE SO GOOD?

Deliciousness is the happy result of a surprising mélange of factors, some of which have nothing to do with your taste buds

By Michael Moyer

TASTE IS NOT WHAT YOU THINK. EVERY SCHOOLCHILD LEARNS THAT IT IS ONE OF THE FIVE senses, a partner of smell and sight and touch, a consequence of food flitting over taste buds that send important signals—sweet or bitter, nutrient or poison?—to the brain. Were it so simple. In the past decade our understanding of taste and flavor has exploded with revelations of the myriad and complex ways that food messes with our consciousness—and of all the ways that our biases filter the taste experience. Deliciousness is both ingrained and learned, both personal and universal. It is a product of all five senses (hearing included) interacting in unexpected ways, those sensory signals subject to gross revision as they are integrated by the brain into one complex, sometimes wonderful perception.

IN BRIEF

Flavor is a complex perception that the brain constructs by combining a wide range of sensory inputs—sights, sounds, smells and textures among them—with memories, social cues and hardwired instincts.

Certain foods taste better together, some scientists believe, when they have a large number of flavor compounds in common. To test this idea, researchers have mapped the chemical connections among common foods.

Photograph by Dan Saelinger

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Research into why we love some foods more than others points to a combination of factors that include, among other things, looks, smells, sounds and even past experiences.

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Let's start at the beginning: Food enters your mouth, meets your teeth and begins to be broken down by enzymes in your saliva. The morsel soon moves over your papillae, the few thousand bumps that line your tongue. ❶

Each papilla houses onionlike structures of 50 to 100 taste cells folded together like the petals of a young flower about to bloom—taste *buds,* we call them. These cells have chemical receptors attuned to the five basic tastes—bitter, sweet, sour, salt and umami, the last a word borrowed from Japanese that describes the savory flavors of roast meat and soy sauce. ❷

These five tastes are enough to help determine if the thing we just put into our mouth should go any farther—if it's sweet or savory and thus a probable source of nutrients or if it's bitter and potentially poisonous. Yet they can't get close to communicating the complexity of the flavors that we sense.

For that, we turn to the nose. As you take in a piece of food, a little air is forced up passageways at the back of the mouth, where scent receptors in the nasal cavity detect thousands of volatile chemicals that add up to complex flavors. This retronasal olfaction, as it is called, has almost nothing to do, physiologically, with the act of sniffing your food. Your brain knows where your smell signals are coming from—through your nostrils or from your mouth. And in the case of the latter, it ropes them together with the signals from the taste buds. Retronasal olfaction produces a completely unique sense—neither smell nor taste alone but a hybrid that we call flavor. It is a process as transformative and irreversible as turning fuel and oxygen into flame.

Our sense of taste doesn't end at the mouth. In recent years scientists have found taste receptors all over the body, discoveries that have solved some longstanding mysteries. For 50 years scientists had been trying to figure out why eating glucose produces a much sharper insulin release than injecting the same amount of

❶ That tongue "taste map" your schoolteachers taught you? Forget it. The map was based on a misunderstood diagram in a 1901 paper.

❷ Some researchers argue that we should expand the list to include fatty, metallic and kokumi, which translates to "mouthfulness" or "heartiness."

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glucose directly into the bloodstream. In 2007 they discovered that cells lining the small intestine also contain taste receptors. When these intestinal sweet sensors detect sugar, they trigger a cascade of hormones that ultimately ends with a squirt of extra insulin into the bloodstream. ❸

Our sense of taste isn't just limited to the mouth and the gut. For example, your nose is lined with cells that sense bitter chemicals. If there is poison in the air, they reflexively stop you from pulling it into your lungs. If the poison does get to the throat, bitter detectors in the trachea trigger cilia to help clear the airway. ❹

This physiology may explain what we mean by flavor—but anatomy doesn't much help us understand what we like. Our flavor preferences take shape over a lifetime, beginning while we are still in the womb. Babies whose mothers consume garlic while pregnant are more likely to enjoy the flavor of garlic in breast milk. Pregnant women who drink carrot juice are more likely to have kids who like carrots. ❺ The evolutionary justification is simple enough: if Mom ate it, it's safe.

Indeed, we use our friends and loved ones in much the same way that medieval monarchs used food tasters—let them try it first, then let's see how they are doing in 20 minutes. The principle holds all the way down the food chain. Rats hate the taste of cocoa, ❻ yet some enterprising scientists recently separated a rat from its brood and coaxed it to eat some anyway. The rat then returned to its group. When the other rats smelled the cocoa on

❸ Amazingly, these taste receptors are just as fooled by artificial sweeteners as your tongue is—NutraSweet also leads to a surge of insulin.

❹ The more they look, the more researchers are finding taste receptors in the most unlikeliest of places. Sweet receptors line the bladder. Your spine has sour receptors. And most bizarrely, the testes have the capacity to sense bitter taste, whereas sperm can detect umami.

❺ The same has been tested for anise, mint, vanilla and every kid's favorite: blue cheese.

❻ The unsweetened variety—too bitter, presumably.

PROP STYLING BY DOMINIQUE BAYNES

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its breath, they changed their minds and suddenly couldn't get enough cocoa.

Children are harder to convince—they have to try an unfamiliar food about nine times, on average, before they begin to like the taste. ❼ As any parent will attest, so much of the eventual enjoyment rests on how well Mom and Dad sell it. Moreover, the same holds true for adults—hence decades of increasingly sophisticated food-marketing campaigns.

The environment sends many cues about how food should taste. In one experiment, researchers connected volunteers' tongues to a low-voltage electrical device, showed them pictures of food items and then sent a mild shock across their taste buds—a sensation not unlike licking a battery. The shock was supposed to impart a neutral taste. Asked afterward to rate how pleasurable the shock was, those volunteers who saw photographs of sweet or fatty foods rated the stimulus far more pleasurable than those who saw a low-calorie food.

The visual and auditory triggers can be so obvious as to appear comical. Potato chips taste crisper if you hear a crunch over headphones. White wine with a drop of red food coloring tastes like red wine—even to experienced wine tasters. People will eat less food off of a red plate. A block of cheese with sharp edges tastes sharper than one with round corners.

It's not all from our mouth, or our mouth and the back of our nose, or our mouth, and nose, and taste cells in the intestine. Deliciousness comes from our mother, our childhood, the room we are eating in, the plates we are eating on and the friends we are eating with. It's mental as much as chemical. Flavor starts in food, yes, but it is also something that is ours to create, everyday. SA

Michael Moyer is deputy editor of Quanta Magazine, an online publication. He was until recently special projects editor at *Scientific American*.

❼ Your mileage may vary.

MORE TO EXPLORE

Taste: Making Sense of Flavour. Special issue of *Nature*, Vol. 486, Supplement, pages S1–S43; June 21, 2012.

Can We Feed the World? The Future of Food. *Scientific American* e-book available from http://books.scientificamerican.com/sa-ebooks

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TASTE MAP

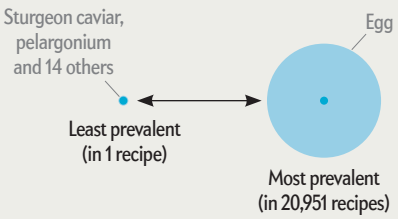
The Flavor Connection

Julia Child famously said that fat carries flavor, but perhaps instead we should give thanks to 4-methylpentanoic acid. Unique combinations of such chemical compounds give foods their characteristic flavors. Science-minded chefs have gone so far as to suggest that seemingly incongruous ingredients—chocolate and blue cheese, for example—will taste great together as long as they have enough flavor compounds in common. Scientists have put this hypothesis to the test by creating a flavor map, a variant of which we have reproduced here. Lines connect foods that have components in common; thick lines mean many components are shared. By comparing the flavor network with various recipe databases, the researchers conclude that chefs do tend to pair ingredients with shared flavor compounds—but only in Western cuisine. Dishes from a database of recipes from East Asia tend to combine ingredients with few overlapping flavors.

How to Read This Graphic

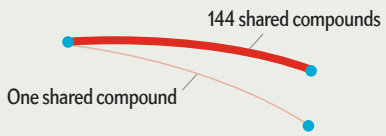
Each blue dot is a food. Similar foods are grouped into 14 category columns (*listed in alphabetical order*).

The size of a dot shows how popular the food is—the frequency with which it appears in a global 56,498-recipe database.



Of all the foods that share flavors outside of their own categories (and excluding roasted peanuts/peanut butter), beer and roasted beef have the most in common: 106. Close behind are apples/white wine and coffee/roasted beef, both with 105.

A line connecting two dots means the two foods share at least one flavor-related chemical compound. The more flavor compounds they share, the thicker the line. Red lines connect foods in different categories.



Wine and cheese contain many of the same flavor-producing chemicals.

Gray lines connect foods in the same category.

A food's vertical position on the page reveals the total number of foods that connect to it. Foods at the top of the page share flavor compounds with many other foods. Foods at the bottom of the page are completely unique—they do not share flavors with any other foods.

Because of space constraints, only the most popular ingredient in a cluster of dots is labeled.

Eggs, flour and butter were the three most popular ingredients, each appearing in more than 20,000 recipes. Rounding out the top 10: onion, garlic, milk, vegetable oil, cream, tomato and olive oil.

SOURCE: "FLAVOR NETWORK AND THE PRINCIPLES OF FOOD PAIRING," BY YONG-YEOL AHN, SEBASTIAN E. AHNERT, JAMES P. BAGROW AND ALBERT-LÁSZLÓ BARABÁSI, IN *SCIENTIFIC REPORTS*, VOL. 1, ARTICLE NO. 196; DECEMBER 15, 2011. WITH THANKS TO SEBASTIAN AHNERT

Graphic by Jan Willem Tulp

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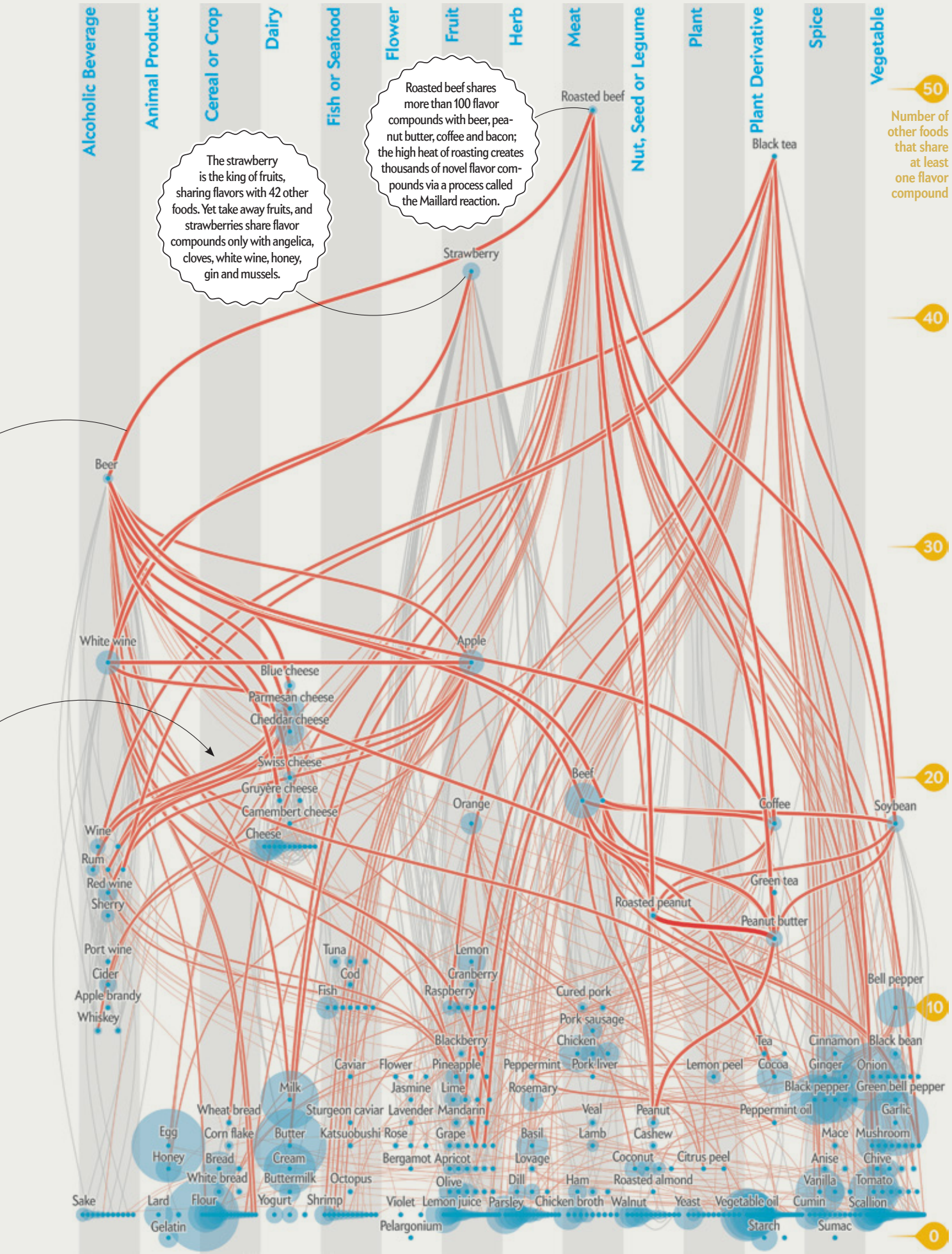

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BIOCHEMISTRY

THE COMPLEXITY OF COFFEE

One of life's simple pleasures is really quite complicated

By Ernesto Illy, with Andrea Illy

FOR SHEER SENSORY ENJOYMENT, FEW EVERYDAY EXPERIENCES CAN COMPETE WITH A GOOD cup of coffee. The alluring aroma of steaming hot coffee just brewed from freshly roasted beans can drag sleepers from bed and pedestrians into cafés. And many millions worldwide would find getting through the day difficult without the jolt of mental clarity imparted by the caffeine in coffee. But underlying this seemingly commonplace beverage is a profound chemical complexity. Without a deep understanding of how the vagaries of bean production, roasting and preparation minutely affect the hundreds of compounds that define coffee's flavor, aroma and body, a quality cup would be an infrequent and random occurrence.

IN BRIEF

Your morning cup of java is the produce of centuries of experimentation with the coffee bean and sophisticated technologies aimed at getting the richest, most satisfying flavor into each sip.

Every stage of preparation en route to your espresso—from the selection, drying and roasting of the beans to the grinding and the high-pressure extraction of the crema—is crucial to quality.

The best beans are individually selected by automated inspectors. The aromas so important to flavor are analyzed using gas chromatographs and mass spectrometers.

Drip and pod machines make good coffee easy. Pulling a truly great espresso shot takes skill—but it helps to have a working knowledge of the biochemistry that makes this beverage so delicious.

JAIME CHARD *Getty Images*

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Connoisseurs agree that the quintessential expression of coffee is espresso: that diminutive, heavy china cup half-filled with a dark, opaque brew topped by a velvety thick, reddish-brown froth called crema. Composed of tiny gas bubbles encased in thin films, the surprisingly persistent crema locks in the coffee's distinctive flavors and aromas and much of its heat as well. Espresso—the word refers to a serving made on request expressly for the occasion—is brewed by rapidly percolating a small quantity of pressurized, heated water through a compressed cake of finely ground roasted coffee. The resulting concentrated liquor contains not only soluble solids but also a diverse array of aromatic substances in a dispersed emulsion of tiny oil droplets, which together give espresso its uniquely rich taste, smell and "mouthfeel."

Aficionados consider perfectly brewed espresso to be the ultimate in coffee because its special preparation amplifies and exhibits the inherent characteristics of the beans. Espresso is useful for our purposes as it is in effect a distillation of all the numerous techniques by which coffee can be made, including the Turkish method and various infusion and filter drip processes [*see box on page 14 for descriptions of alternative methods for preparing coffee*]. To know espresso is to know coffee in all its forms.

High-quality coffee arises from maintaining close control over a multitude of factors in the field, in the plant and in the cup. Coffee cultivation entails myriad variables that must be monitored and regulated. Once a coffee bean is grown, nothing can be added or removed: the quality must already be present. For a single portion of espresso, 50 to 55 roasted coffee beans are required; a single imperfect bean will taint the whole sufficiently to be noticeable. This is because human olfaction and taste senses originated as defense mechanisms that protected our ancestors from rotten—hence, unhealthy—foods. Only through modern technology can one economically and consistently identify 50 nearly perfect beans.

GROWING COFFEE

RAW COFFEE BEANS are the seeds of plants belonging to the Rubiaceae family, which comprises at least 100 species of the genus *Coffea*. The two species that are commercially exploited are *Coffea arabica,* which accounts for two thirds of world production, and *Coffea canephora,* often called robusta coffee, with one third of global output. Robusta coffee plants and all wild coffee species have 22 chromosomes, whereas arabica has 44. Therefore, arabica cannot be crossed with other coffee species to produce a hybrid plant.

Robusta is a high-yielding and disease-resistant tree standing up to 12 meters tall that grows best in warm, humid climes. It produces a cup featuring substantial body, a relatively harsh, earthy aroma, and an elevated caffeine content that ranges from 2.4 to 2.8 percent by weight. Although robusta is sold by many purveyors, it does not give rise to the highest-quality coffee.

Arabica, which originated in the Ethiopian highlands, is a medium- to low-yielding, rather delicate tree from five to six meters tall that requires a temperate climate and considerable growing care. Commercially grown coffee bushes are pruned to a height of 1.5 to 2.0 meters.

TIMELINE

From Kefa to Cafe

People have enjoyed the flavors and stimulative kick of coffee for thousands of years. And in many parts of the world, the beverage is still growing in popularity.

1000 B.C. to A.D. 500 The nomadic Oromos tribe, living in the kingdom of Kefa (in modern-day Ethiopia), eat coffee, crushed, mixed with fat and shaped into golf ball–size portions, as a pick-me-up.

Circa 600 Coffee is brought by traders across the Red Sea into Arabia (modern-day Yemen).

Late 1400s to early 1500s Coffee beans, heretofore an Arabian monopoly, are brought to Turkey, Egypt and Syria by Muslim pilgrims returning from Mecca. Arabian-influenced coffeehouses open in Constantinople, Damascus and other Near Eastern cities, where European traders, particularly Venetians, are introduced to the beverage.

Circa 1600 Calling it "the bitter invention of Satan," advisers urge Pope Clement VIII to reject the favorite drink of the infidel Ottoman Turks. Instead he decides to give papal authority to coffee, making it acceptable for Roman Catholics.

1616 Dutch entrepreneurs start to cultivate coffee commercially, beginning with a coffee plant obtained from Yemen. By 1658 (according to some sources, the 1690s), the Dutch are growing coffee in Ceylon and their East Indian colony of Java.

1714 The mayor of Amsterdam presents the French king, Louis XIV, with a coffee plant from Java.

1723 Gabriel Mathieu de Clieu, a French naval officer, carries three coffee seedlings obtained under questionable circumstances from the Royal Botanical Gardens on a perilous voyage to the Caribbean island of Martinique, where one of the plants thrives.

1727 After having been called to arbitrate a border dispute between two coffee-growing colonies, Dutch Guiana and French Guiana, Francisco de Melo Palheta, a Portuguese Brazilian official, smuggles several coffee seedlings to his home estates.

1903 German coffee importer Ludwig Roselius perfects decaffeinated coffee.

1933 Francesco Illy patents the first automatic espresso machine.

1961 Ernesto Valente of Faema, an Italian coffee machine maker, designs the archetype of the modern espresso machine.

2014 With more than 700 billion cups consumed every year, coffee may be the world's most popular beverage (besides water, of course).

Coffee ranks second only to petroleum in terms of dollars traded worldwide. The International Coffee Organization estimates that exports of coffee in 2014 totaled 6.7 billion kilograms, worth at least $18 billion.

Controversy continues over whether shade-grown coffee should be promoted to enhance bird habitats.

According to a survey of 2,741 Americans conducted by the National Coffee Association in 2014:

Sixty-one percent of adults (older than 18 years) in the U.S. drink coffee every day, representing 148 million daily drinkers. Another 18 percent of adults (44 million) drink coffee at least once a year.

American coffee drinkers consume, on average, 3.4 (nine-ounce) cups of coffee a day.

Coffee and caffeine have been the subject of extensive scientific study during the past quarter of a century, with 1,500 to 2,000 papers published every year on the topic. Despite this close scrutiny, few negative health effects have been definitively linked to the moderate consumption (two cups a day) of caffeinated coffee. On the contrary, recent epidemiological studies have observed that coffee consumption is associated with a lower risk of several diseases.

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Coffee made from arabica beans has an intense, intricate aroma that can be reminiscent of flowers, fruit, honey, chocolate, caramel or toasted bread. Its caffeine content never exceeds 1.5 percent by weight. Because of its superior quality and taste, arabica sells for a higher price than its hardy, rougher cousin.

A good rainfall induces arabica coffee plants to blossom, and some 210 days afterward red or yellow fruit called cherries appear. Each cherry contains two oblong seeds—the coffee beans. Because both fruit and flower can be present simultaneously on the same branch, the picker's forefinger and thumb are the best tools to gather just the ripe cherries. Stripping entire branches by hand or using automated harvesting machines does not discriminate between the ripe and the unripe cherries.

The ultimate quality of the resulting coffee beans depends on the genetics of the plant, the soil in which it grows and the microclimate, which encompasses factors such as altitude, the amount of rainfall and sunlight, and daily temperature fluctuations. Along with the roasting processes that are applied, these agricultural and geographical considerations are responsible for the taste differences among the many kinds of coffee beans that suppliers combine to produce the various distinctive blends one can purchase.

FROM CHERRY TO BEAN

COFFEE CHERRIES must be processed immediately after harvest to prevent spoilage. Producers either sun-dry the cherries or wash them. Sun-drying involves spreading the cherries out on a patio and stirring the desiccating fruit frequently to evenly heat and aerate them. The dried cherries are run through a machine that crushes the hulls and then removes both the hulls and the surrounding parchment membrane layer, thus freeing the beans for sorting and bagging. In the alternative approach, the fruit is mechanically pulped, washed, and finally dried and liberated from the parchment covering. The goal of either route is the same: the 65 percent water content of the coffee cherry is reduced to the 10 to 12 percent moisture level of a prime raw, or green, coffee bean.

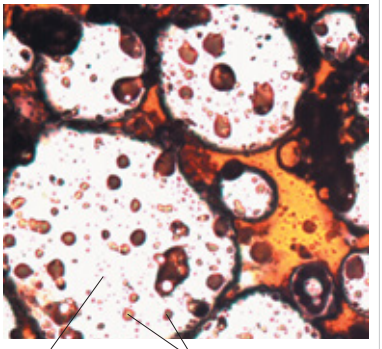
One of the greatest challenges in producing superior coffee is ensuring that one starts with exceptional green beans. Premium producers, such as illycaffè, our company based in Trieste, Italy, use many sophisticated process-control techniques to minimize the percentage of defective coffee beans, including ultraviolet fluorescence analysis to spot moldy beans and trichromatic mapping to generate a color fingerprint (yellow-green, red and infrared) of each lot of beans. At illycaffè, a dichromatic sorting system developed

ILLYCAFFÈ (*micrograph*); NINA FINKEL (*illustrations*)

BEHIND THE BUZZ

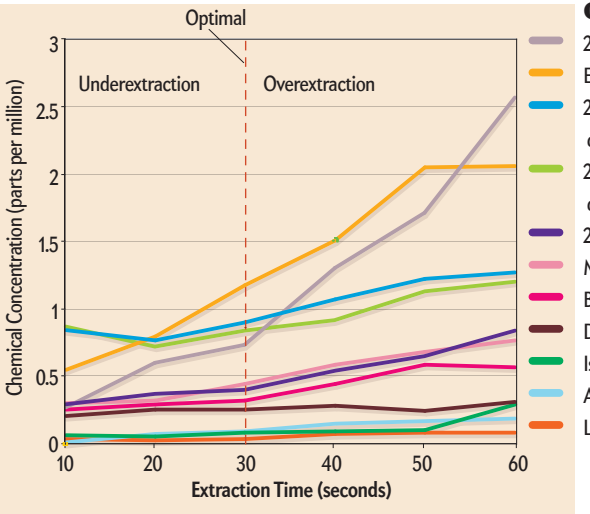
Coffee Chemistry

A perfect cup depends on what is in the beans (*bottom*) and how it is brewed (*right* and *below*). Crema, the dense, reddish-brown foam that tops an espresso, is seen in an enlarged cross section at the right. Composed mainly of tiny carbon dioxide and water-vapor bubbles (*large circles*) surrounded by surfactant films, it also includes emulsified oils containing key aroma compounds (*particles with red borders*) and dark fragments of the coffee bean cells.



How the Chemical Composition of Espresso Depends on the Extraction Time

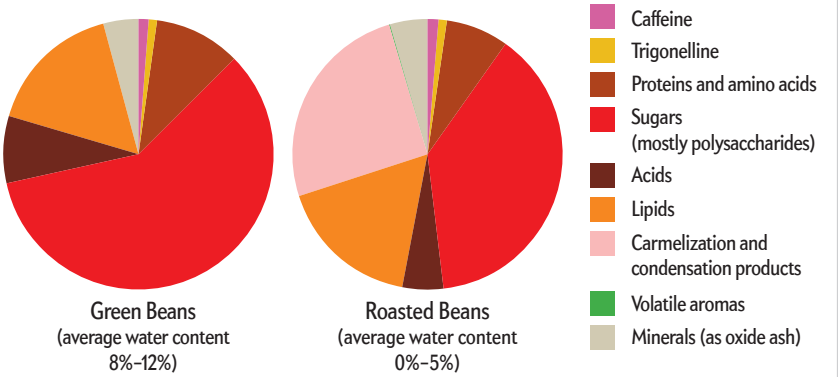
As hot water is forced through coffee grounds, the concentration of undesirable, less soluble aroma compounds (*red type*) rises. A 30-second extraction produces the optimal flavor.



Compound	Aroma
2,4-decadienal	Rancid
Ethylgujacol	Smoke
2-ethyl-3,5-dimethylpyrazine	Chocolate
2-ethyl-3,6-dimethylpyrazine	Chocolate
2,4-nonadienal	Rancid
Methylsalicilate	Cinnamon
B-damascenone	Tea
DMTS	Sulfur
Isovaleraldehyde	Sweet
A-ionone	Flowers
Linalool	Flowers

Composition of Raw and Roasted Arabica Coffee (percentage of dry matter)

Roasting improves the flavor of green beans by caramelizing sugars and reducing acids.



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OTHER TECHNIQUES

Coffee by the Pot—or Pod

Filter drip (Chemex, Melitta, auto drip) coffee was invented by the French in the early 18th century and improved in 1908 by Melitta Benz, who introduced the paper filter. Automatic and manual drip coffee makers yield results that vary from light- to heavy-bodied, depending on the shape and material of filter used. One tablespoon of medium-fine coffee grounds is added to the filter for every 10 ounces of water. When prepared manually, hot water is slowly poured over the grounds until the desired volume is reached. Filter drip coffee has a well-balanced, clean taste.

Pods and capsules are designed to deliver a single portion of coffee with consistency and ease. Two kinds of capsules are common. One simply holds ground coffee through which water passes to extract the brew. The other is a two-phase system. First a coffee-filled capsule is infused with water under pressure. An emulsion phase then follows and creates an espresso having a pleasantly thick crema.

Turkish coffee is full-bodied, thick and sweet. It is prepared in an Ibrik, a copper/brass pot with a long handle. One tablespoon of coffee, ground to a fine powder, is added for every three ounces of water (and often generous helpings of sugar). Placed on medium heat, the Ibrik will begin frothing slightly. The coffee is then gently stirred. The process of slow heating and stirring is repeated twice. Turkish coffee is served in a demitasse.

French press coffee originated in France around 1852 and was later refined by Italians. One tablespoon of medium-coarse grounds is used for every four ounces of water. After the hot water (not boiling) is added, the coffee should steep for two to four minutes. The grounds are then forced to the bottom of the pot by pressing down on a metal mesh filter. The result is a full-bodied, bold coffee.

in collaboration with the English company Sortex is applied as a final control right before roasting. As beans fall into bins, photoelectric CCD cameras detect duds, signaling for them to be rejected individually with a puff from an air nozzle. The sorting operation is accomplished at a speed that no human hand can match (22,000 beans a second by a 64-chute machine) and with a precision that exceeds that of even the most highly trained eye.

A perfect mature green coffee bean is composed of cells having uncommonly thick walls: as much as seven microns, an exception in the vegetal kingdom. During roasting, these 30- to 40-micron-diameter cells serve as tiny reactors in which all of the crucial, heat-driven chemical reactions that generate coffee's seductive taste and fragrance occur. The cells of immature beans have thinner walls. Unripe beans also lack the important aromatic precursor proteins that develop in the last stages of the ripening process. Fermented beans are composed of cells that have been emptied of these crucial constituents by molds or bacteria.

THE SCIENCE OF ROASTING

ROASTING is a pyrolytic (heat-driven) process that greatly increases the chemical complexity of coffee. The aroma of green coffee contains some 250 different volatile molecular species, whereas roasted coffee gives rise to more than 1,000.

When subjected to the staged heating of a roasting machine (basically, a huge, hot, rotating cylinder), residual water inside each cell boils into steam, which promotes diverse, complicated chemical reactions among the cornucopia of sugars, proteins, lipids and minerals within [*see box on preceding page*]. At high heat, from 185 to 240 degrees Celsius, sugars combine with amino acids, peptides and proteins, following well-known processes such as caramelization and the Maillard reaction. The end products are brownish, bittersweet glycosylamine and melanoidins—which give rise to coffee's dominant taste—along with carbon dioxide.

Simultaneously, a wide variety of lighter aroma compounds emerge; these volatile molecules give coffee its familiar fragrance. Pressure inside each cell increases to 20 to 25 atmospheres as the steam and carbon dioxide try to escape but are sealed in by the thick, nearly impermeable cell walls and a thin film of oil. Some cells eventually burst, creating the characteristic popping sound of roasting coffee. Roasting boosts beans' volume by half or more and decreases their mass by a fifth.

Depending on the temperatures and procedures applied, the roasting process can last from 90 seconds to 40 minutes. Twelve minutes is the traditional duration. The thermodynamics of the intracellular reactions differ according to roasting time, and so does the final result. A short roasting time, which requires a great deal of thermal energy, minimizes weight loss but imparts to the cup a metallic bitterness resulting from the presence of polyphenols that do not have enough time to react properly. Long roasting periods, frequently used in poorer countries in which many consumers can afford only low-priced, defective beans, forces all the off-flavors and fragrances to leave the beans. Sadly, the desirable tastes and aromas flee as well, yielding a rather bitter cup.

CHRIS KOLBU Getty Images

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The higher the final temperature of the roasting, the less desirable the aroma will be, and the stronger the bitterness. Conversely, low roasting temperatures fail to develop fully the welcome aromas, and acidity tends to come to the fore.

AN AROMA LIKE NO OTHER

AROMA SCIENCE is highly complex. Researchers typically analyze the fragrances evolved during coffee bean roasting by gas chromatography coupled with olfactometry, in which skilled testers sniff and define the smell of each recognizable element. Mass spectrometry is frequently then applied to identify the chemical composition of each odor. Sniffing roasted coffee aromas that have been fractionated by a gas chromatograph is an enlightening experience: one may recognize the aromas of roses, Darjeeling tea, chocolate, vanilla and violets, as well as truffles, soup, cheese, sweat and even what is called cat scent, which, if diluted, smells like sauvignon blanc wine but in a concentrated sample is disgusting.

At illycaffè, technicians focus on the strongest odorants. Imagine listening to a recording of a choir of 800 singers that includes the strong solo voices of Jessye Norman, Luciano Pavarotti and several other virtuosi who tend to dominate the ensemble. If the volume of the playback is reduced, the stronger voices will still be recognizable even as the choir's sound fades away. Diluting the aroma of coffee is analogous; beyond a certain point, only the strongest compounds are perceived. Unfortunately, the most powerful molecules in the smell of a coffee sample are those originating from defective beans.

Molecules such as ethylbutanoate and ethylglycolate, which are responsible for the unpleasant aroma of immature beans, ruin a cup of coffee by their very presence. Likewise, methylisoborneol and trichloroanisole (TCA) molecules produce the characteristic earthy, chemical smell of robusta coffees. TCA, which is also called Rio taste because it was first discovered in coffees grown around Rio de Janeiro, can be found in corked wines as well. Its perception threshold to the human olfactory system is shockingly low—six millionths of a billionth of a gram per milliliter.

EXTRACTING THE BREW

THE NEXT MAJOR STEP in the transformation of roasted beans into a cup of espresso is the extraction of the active components in the roasted and ground coffee by heated water. The interaction of hot water and coffee grounds is, however, subtly different when making common drip coffee than when making espresso.

When filter drip coffee is prepared, hot water passes through a loose aggregation of medium-size coffee grounds. During the four to six minutes of contact with the boiling water, most of the soluble substances present in the roasted coffee pass into solution. Thus, large quantities of highly soluble acids and caffeine dissolve into the cup. In contrast, the much shorter percolation time of espresso allows less acid and only 60 to 70 percent of the caffeine to dissolve into the brew.

Brewing espresso requires specialized equipment that can heat water to a temperature of 92 to 94 degrees C and pressurize it to nine atmospheres. Coffee, ground to a fine to medium consistency, is placed in a perforated basket and firmly tamped down to create a compacted bed of particles. The compressed grounds adhere to one another thanks to a thin coating of oil, which is as viscous as honey. The oil binds the particles together into a condensed maze of minuscule air passages. Experimentation has shown that the hydraulic resistance of this bed of coffee grounds must be slightly less than the pressure of the steaming-hot extraction water, allowing it to flow through at a rate of around a milliliter a second.

Using the recommended 30 seconds of percolation, a skilled barista (coffee bar technician) produces about 30 milliliters of dense coffee liquor covered by the all-important crema. If the color of the foam topping is light, it means that the espresso has been underextracted, probably because the grind was too coarse, the water temperature too low or the time too short. If the crema is very dark in hue and has a "hole" in the middle, it is likely that the consistency of the coffee grounds was too fine or the quantity of grounds was too large. An overextracted espresso exhibits either a white froth with large bubbles if the water was too hot or just a white spot in the center of the cup if the brewing time was too long.

The percolation process also washes out components present on the surface of the coffee grounds, including aroma-filled oil and bits of the cellular structure. The high pressure generated by the espresso machine emulsifies a small amount of the oils, about 0.1 gram a cup. Intact cells in the grounds create a fine effervescence, which is derived from gases (especially carbon dioxide) passing through tiny pores in the cell walls. Some very fine grounds can also find their way into the beverage, along with cell wall fragments, which endow the foamy crema with what is called the tiger-skin look.

The final result is a polyphasic colloidal system, in which water molecules are bound to the dispersed gas bubbles, oil droplets and solid fragments, all of which are less than five microns in size. The colloidal character of the dispersion gives the drink high body, high viscosity and low surface tension. Espresso thus visibly coats our tongues and continues to release the aromatic volatiles dissolved in the emulsified oils as long as it remains there. These oily flavor/fragrance carriers mean that the great taste and aroma of a good espresso can be savored for as long as 20 minutes after it has been drunk. Luckily, the drinker need not know anything about the complex chemistry of coffee to enjoy it. SA

Ernesto Illy was chairman of illycaffè, a family business based in Trieste, Italy, from 1963 to 2004. He died in 2008. This article, written by Ernesto Illy in 2002, was updated for this issue by his son Andrea, who is the current chairman of illycaffè. Over six million illy espressos are served every day in more than 140 countries around the world.

MORE TO EXPLORE

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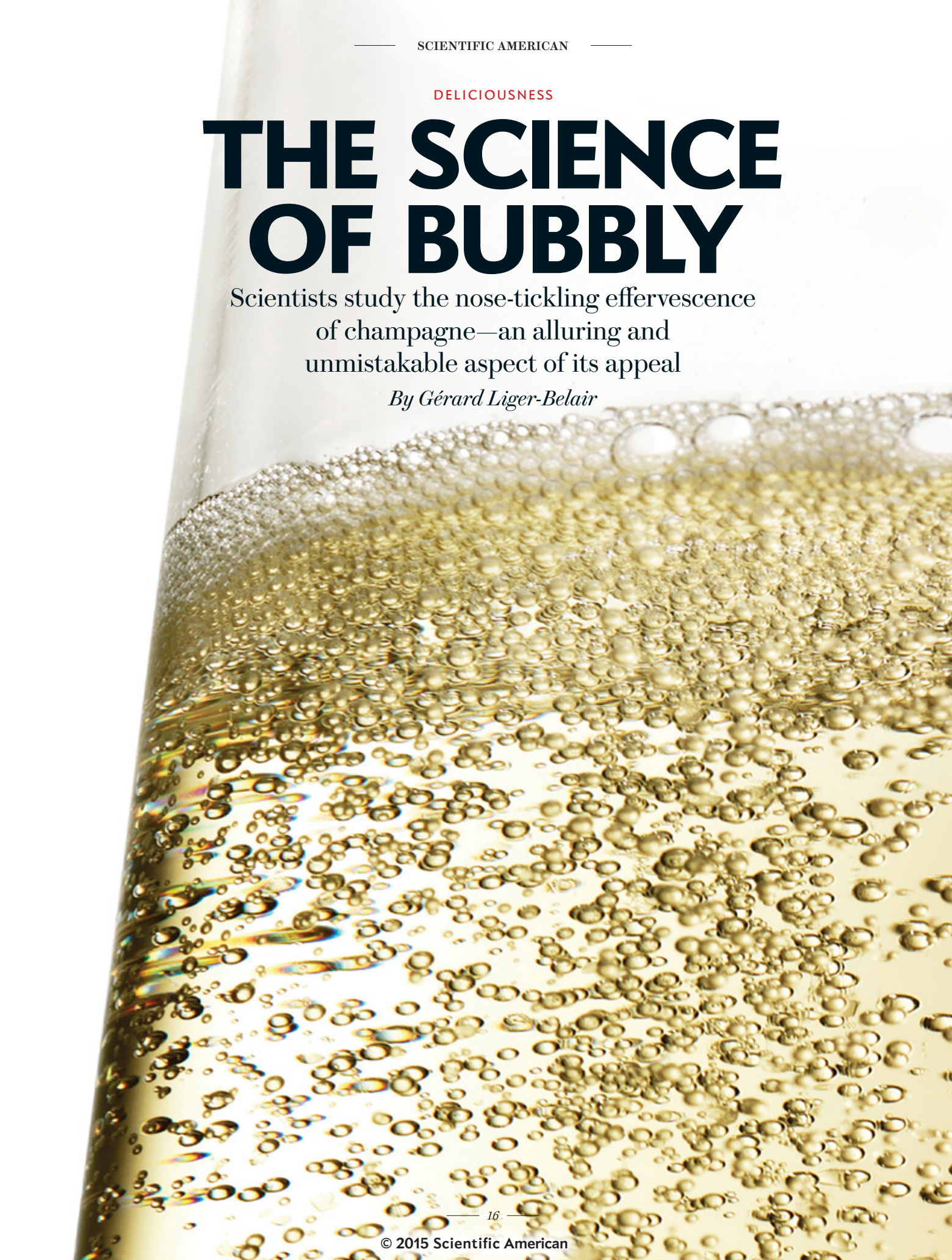
DELICIOUSNESS

THE SCIENCE OF BUBBLY

Scientists study the nose-tickling effervescence of champagne—an alluring and unmistakable aspect of its appeal

By Gérard Liger-Belair



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POP OPEN A BOTTLE OF CHAMPAGNE AND POUR YOURSELF A GLASS. TAKE A SIP. THE elegant surface fizz—a boiling fumarole of rising and collapsing bubbles—launches thousands of golden droplets into the air, conveying the wine's enticing flavors and aromas to tongue and nostrils alike. A percussive symphony of diminutive pops accompanies the tasty mouthful, juxtaposing a refreshing carbonated chill and a comforting alcoholic warmth. Such is the enchantment of bubbly, the classic sparkling wine of northeastern France's Champagne district, a libation that has become a fixture at festive celebrations worldwide. Among the hallmarks of a good champagne are multiple bubble trains rising in lines from the sides of a poured glass like so many tiny hot-air balloons. When they reach the surface, the bubbles form a ring, the so-called *collerette,* at the top of a filled flute. Although no scientific evidence correlates the quality of a champagne with the fineness of its bubbles, people nonetheless often connect the two. Because ensuring the traditional effervescent personality of champagne is big business, it has become important for vintners of sparkling wines to achieve the perfect *petite* bubble. More than a decade ago several research colleagues from the University of Reims Champagne-Ardenne and Moët & Chandon and I decided to examine the behavior of bubbles in carbonated beverages. Our goal was to elucidate the roles of each of the many parameters that come into play in bubbling. Close observations of glasses filled with sparkling wine, beer and soda revealed their visually appealing outgassing to be surprisingly complex. In the years since, we have learned a great deal about the three main phases of a bubble's life: its birth, ascent and dramatic demise.

On the rise: The short but spectacular ascent of champagne bubbles to the top of a glass embodies a complex physicochemical system that is both more functional and more picturesque than one might expect.

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BUBBLE GENESIS

IN CHAMPAGNE, sparkling wines and beers, carbon dioxide (CO_2) is the principal agent that produces gas bubbles, which form when yeast ferments sugars, converting them into alcohol and carbon dioxide molecules. Industrial carbonation is the source of the fizz in soda drinks. After bottling or canning, the carbon dioxide dissolved in the liquid comes into equilibrium with the gas in the space directly under the cork, cap or tab.

When the container is opened, the pressure of the gaseous carbon dioxide above the liquid falls abruptly, breaking that equilibrium. As a result, the liquid becomes supersaturated with carbon dioxide. To regain thermodynamic balance with the CO_2 in the atmosphere, carbon dioxide must leave the fluid. When the beverage is poured into a glass, two mechanisms enable dissolved carbon dioxide to escape: diffusion through the free surface of the liquid and bubble formation.

Before molecules of gas can coalesce into embryonic bubbles, however, they must push their way through the liquid, the molecules of which are strongly linked by van der Waals forces (dipole attraction). Bubble formation is limited by this energy barrier; the supersaturation that occurs in carbonated beverages is not strong enough to overcome it alone.

In weakly supersaturated liquids, including champagne, sparkling wines, beers and sodas, bubbles thus form only when preexisting gas cavities are large enough to overcome the nucleation energy barrier. The cavities must be big because the curvature of the gas/liquid interface leads to an excess of pressure inside the gas pocket that is inversely proportional to its radius. The smaller the bubble, the greater the overpressure within it. CO_2 simply cannot diffuse into bubbles smaller than a critical size. In newly opened champagne, the critical radius is microscopic—around 200 nanometers.

To observe "bubble nurseries" in detail, we aimed a high-speed video camera fitted with a microscope objective lens at the bases of hundreds of bubble trains. Contrary to general belief, these nucleation sites are not located on irregularities on the glass surface, which are much smaller than the critical radii of curvature required for bubble formation. Bubble nurseries, it turns out, arise on impurities *attached* to the glass wall. Most are hollow cellulose fibers that fell out of the air or were left behind as the glass was wiped dry. The geometries of these fiber particles prevents them from being wet completely by the beverage. They are thus able to entrap gas pockets when a glass is filled [*see bottom inset on opposite page*].

A bubble forms when dissolved carbon dioxide molecules migrate into one of these minute gas pockets. Eventually it grows to macroscopic size, yet initially it remains rooted to its nucleation site by capillary forces. Finally the bubble's increasing buoyancy causes it to detach, and a new bubble can form in its place. The process repeats until too little dissolved CO_2 remains to make bubbles.

My colleagues and I use a stroboscope to measure the number of bubbles produced per second at each nucleation site. When the frequency of the flash equals that of bubble production, the bubble train appears frozen.

Because bubble growth depends also on the concentration of dissolved carbon dioxide content, bubble formation frequencies vary from one carbonated beverage to another. In champagne, for example, the most active nucleation sites emit up to about 30 bubbles per second. The gas content of beer is about a third that of champagne, and beer bubble nurseries produce bubbles only about a third as fast.

BUBBLE ASCENT

AFTER A BUBBLE is released from its nursery, it grows as it rises to the surface [*see middle inset on opposite page*]. Carbon dioxide molecules continuously diffuse from the liquid into the bubble as it floats along. As bubbles expand, they become more buoyant, so they accelerate upward and separate from one another.

Bubbles in beers and sparkling wines are more than just pockets of gas because these beverages are not pure liquids. In addition to water, alcohol and dissolved carbon dioxide, the drinks contain proteins, glycoproteins, and other organic compounds that can behave like detergents, also known as surfactants.

Surfactant compounds combine water-soluble and water-insoluble parts. The surfactants come out of solution and encircle bubbles, aiming their hydrophobic ends into the gas and sticking their hydrophilic ends into the liquid.

The surfactant coating changes how a bubble plows its way through the liquid after it detaches. The shieldlike coat stiffens the bubble, which makes it encounter greater resistance from the liquid, compared with a more flexible, surfactant-free sphere. In addition, surfactant molecules encountered during ascent gradually collect on the bubble surface, making it more rigid still. The hydrodynamic drag experienced by a rising bubble of fixed radius thus increases progressively; the bubble slows to a minimum velocity when the gas/liquid interface becomes almost totally contaminated by surfactants.

That is not necessarily true for bubbles that expand as they rise, however. A growing bubble adds surface area, which offers more space to adsorb surfactants. Swelling bubbles are consequently subject to opposing effects. If the expansion rate overcomes the speed with which surfactants stiffen the surface, a bubble "cleans" its interface constantly because the ratio of the surface area covered by surfactants to that free from surface-active agents decreases. If this ratio instead increases, the bubble surface becomes inexorably contaminated by a surfactant monolayer and grows rigid.

My co-workers and I measured the drag coefficients of expanding champagne and beer bubbles during their journeys up to the surface and then compared our data

IN BRIEF

A million bubbles, roughly speaking, appear when you pour a glass of sparkling wine. Bubbles like these are what give beer, champagne and soda their pleasing fizz.

The life cycle of a bubble in a carbonated beverage is more complex than you might think. The bubbles are born, for example, from bits of dust. They are initially a mere 200 nanometers across.

As bubbles rise, gas continually diffuses into them, so the bubbles expand. But soaplike compounds in the liquid coat the bubbles, stiffen their walls and add drag that slows their ascent.

A bubble dies a spectacular death as it bursts and jets aromatic aerosols into the nose and palate of the drinker. The sting and smell of the fizz enhance the flavor of the beverage.

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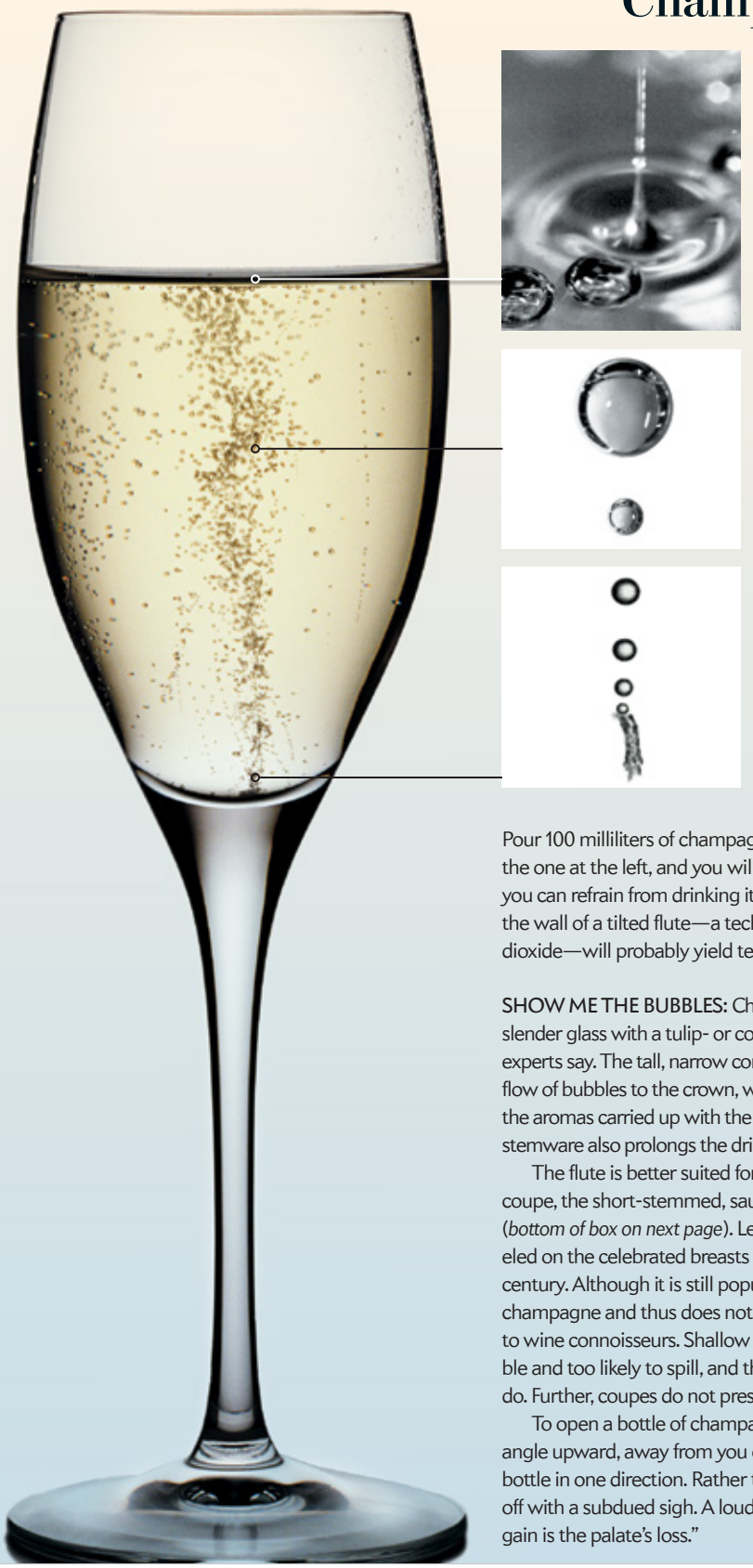
A CLOSER LOOK

Champagne Bubbles



GROWING BUBBLES: The brief existence of a champagne bubble begins on a tiny mote of cellulose left clinging to the sides of a glass after it is wiped dry. When the sparkling wine is poured, a submicron-diameter gas pocket forms on the cellulose fiber. Dissolved carbon dioxide under pressure enters this small cavity and eventually expands it so much that buoyancy causes it to separate from the nucleation site (*bottom inset*). During its journey to the surface, the bubble continues to swell as more carbon dioxide makes its way in (*middle inset*). Simultaneously, aromatic flavor molecules in the beverage attach themselves to the gas/water membrane, a phenomenon that slows the bubble's ascent by boosting its drag. Soon after emerging at the surface, the flavor-carrying gas capsule collapses on itself and shoots a bit of the wine into the air (*top inset*), thus enhancing the champagne's smell and savor.

HOW MANY BUBBLES IN THAT GLASS? Many champagne drinkers have idly mulled this question, but researchers have recently attempted to answer it scientifically by using models that include both the dynamics of bubble ascension and mass transfer equations. As one might expect, the number of bubbles likely to form per glass depends on both the wine and the glass itself. Pour 100 milliliters of champagne straight down the middle of a vertical flute like the one at the left, and you will probably see a million bubbles form in the wine, if you can refrain from drinking it. Champagne served more gently by pouring down the wall of a tilted flute—a technique that better preserves the dissolved carbon dioxide—will probably yield tens of thousands more bubbles before it goes flat.

SHOW ME THE BUBBLES: Champagne is best served in a long-stemmed flute—a slender glass with a tulip- or cone-shaped bowl containing six ounces or more, wine experts say. The tall, narrow configuration of the flute extends and highlights the flow of bubbles to the crown, where the restricted open surface area concentrates the aromas carried up with the bubbles and released by their collapse. The slender stemware also prolongs the drink's chill and helps to retain its effervescence.

The flute is better suited for drinking sparkling wine than the "champagne" coupe, the short-stemmed, saucer-shaped glasses that were once so fashionable (*bottom of box on next page*). Legend has it that these glasses were originally modeled on the celebrated breasts of Marie Antoinette, queen of France in the late 18th century. Although it is still popular, the coupe was never designed for drinking champagne and thus does not allow the taster to fully enjoy its qualities, according to wine connoisseurs. Shallow and wide-brimmed, coupe glasses tend to be unstable and too likely to spill, and they fail to keep the wine as cold as tall wine flutes do. Further, coupes do not present the elegant bubble trains to best advantage.

To open a bottle of champagne, hold it with the cork pointed at a 45-degree angle upward, away from you or anyone else. Hold the cork and gently turn the bottle in one direction. Rather than popping off with a bang, the cork should come off with a subdued sigh. A loud pop wastes bubbles; as the saying goes, "The ear's gain is the palate's loss."

—*G.L.-B.*

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THIS PAGE: EISENHUT & MAYER *Getty Images*; COURTESY OF GERARD LIGER-BELAIR (*insets*)

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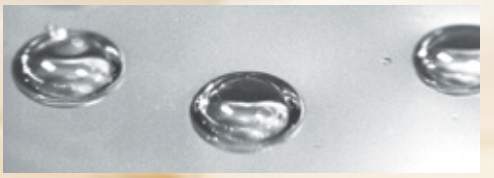
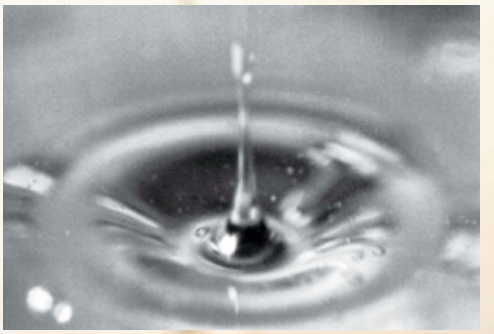
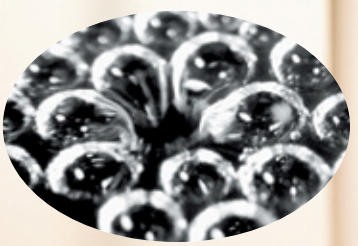
Death of a Bubble

POP GOES THE BUBBLE: The collapse of a champagne bubble begins nearly as soon as it breaches the surface of the beverage (*sequence at right*). In the second image, the thin liquid film that constitutes the emerged part of the bubble has just ruptured. During this extremely brief event, the shape of the bubble—nearly a millimeter wide—remains intact. The collapse of the cavity gives rise to a high-speed liquid jet that flies above the surface (*third image*). Because of its own velocity, this jet becomes unstable, forming a capillary wave that breaks up the flow into droplets. Hundreds of bubbles are bursting every second after pouring, so the liquid surface is literally spiked with cone-shaped structures, which are unfortunately too short-lived to be seen with the naked eye.







BUBBLE FLORETS: Because surface bubbles collapse so rapidly (in less than 100 microseconds), few photographs capture the process. But clusters of champagne bubbles form visually appealing flower-shaped structures (*left*) when they are deformed by the sucking force created by a nearby popped bubble. The bubble caps adjacent to the bubble-free central zones are stretched into teardrop shapes pointed toward the empty cavities.

THE SCIENCE OF FOOD

THINKSTOCK (*wineglass*); COURTESY OF GÉRARD LIGER-BELAIR (*top left, top right* and *bottom right*); FROM "RECENT ADVANCES IN THE SCIENCE OF CHAMPAGNE BUBBLES," BY GÉRARD LIGER-BELAIR ET AL., IN *CHEMICAL SOCIETY REVIEWS*, VOL. 37, NO. 11; JULY 2008 (*bottom left, two at middle right and opposite page*)

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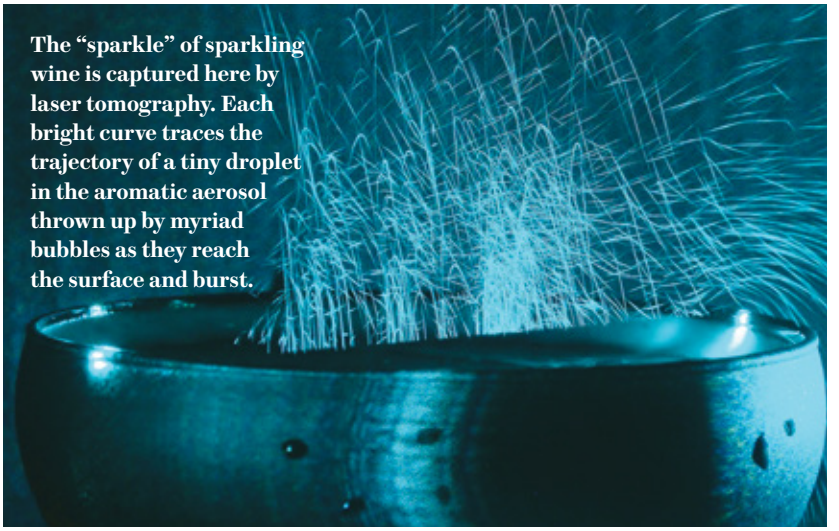
with values found in the scientific literature of bubble dynamics. We concluded that beer bubbles act very much like rigid spheres. In contrast, bubbles in champagne, sparkling wines and sodas present a more flexible interface during their ascent. This is not overly surprising, because beer contains much higher quantities of surfactant macromolecules (on the order of several hundred milligrams per liter) than does champagne (only a few mg/L). Furthermore, because beer contains less gas, beer bubbles grow slower than champagne bubbles do. As a result, the cleaning effect caused by a beer bubble's expansion may be too weak to avoid rigidification of its gas/liquid interface. In champagne, sparkling wines and sodas, bubbles grow rapidly, and the concentration of surfactants is too low to make them rigid.

A NEW VIEW



The "sparkle" of sparkling wine is captured here by laser tomography. Each bright curve traces the trajectory of a tiny droplet in the aromatic aerosol thrown up by myriad bubbles as they reach the surface and burst.

BUBBLE COLLAPSE

IN THE SEVERAL SECONDS after its birth and release, a bubble travels the few centimeters to the beverage's surface, eventually ballooning to a diameter of about one millimeter. Like an iceberg, a gas bubble at the top of a drink emerges only slightly from the surface; most of its volume remains below. The emerged part, the bubble cap, is a hemispherical liquid film that gets progressively thinner as liquid drains down the sides. When the cap thins to a critical thickness, it becomes sensitive to vibrations and thermal gradients, which finally cause it to burst. In 1959 two physicists, Geoffrey Ingram Taylor of the University of Cambridge and Fred E. C. Culick of the California Institute of Technology, showed independently that surface tension causes a hole to appear in the bubble cap and that the hole widens very quickly. For bubbles a millimeter across, disintegration takes only 10 to 100 microseconds [*see box on opposite page*].

After the bubble cap breaks, a complex hydrodynamic process ensues, causing the collapse of the submerged part of the bubble. For an instant, an open cavity remains in the liquid surface. Then the inrushing sides of the cavity meet and eject a high-speed liquid jet above the free surface. Because of its high velocity, this jet becomes unstable, developing a capillary wave (the Rayleigh-Plateau instability) that fragments it into droplets called jet drops. The combined effects of inertia and surface tension give the detaching jet drops a variety of often surprising shapes. Finally they take on a quasi-spherical shape. Because hundreds of bubbles are bursting each second, the beverage surface is spiked with transient conical structures, which are too short-lived to be seen with the unaided eye.

AROMA AND FLAVOR RELEASE

BEYOND AESTHETIC considerations, bubbles bursting at the free surface impart what merchants call "feel" to champagne, sparkling wines, beers and many other beverages. Jet drops are launched at several meters per second up to a few centimeters above the surface, where they come in contact with human sense organs. Nociceptors (pain receptors) in the nose are thus stimulated during tasting, as are touch receptors in the mouth when bubbles burst over the tongue; this bursting also yields a slightly acidic aqueous solution.

In addition to mechanical stimulation, bubbles collapsing at the surface are believed to play a major role in the release of flavors and aromas. Fatty acids and other aromatic compounds in carbonated beverages act as surfactants, so they latch onto rising bubbles, and then molecules concentrate at the surface of the beverage. The aerosol spray created by the bursting of myriad bubbles consists of clouds of tiny droplets. My research group has used ultrahigh-resolution mass spectrometry to analyze the aerosols, and we showed that they contain high concentrations of compounds known to be aromatic or the precursors of aromas. This discovery supports the idea that rising and collapsing bubbles act like an escalator to continuously lift delicious aromas from the glass to the nose and the palate. SA

Gérard Liger-Belair is a professor at the University of Reims Champagne-Ardenne in France, where he studies the physical chemistry of bubbles in carbonated beverages. He also consults for champagne vintners, including Moët & Chandon, Veuve Clicquot and Pommery. Liger-Belair splits his time between the science of bubbles and high-speed imaging, the results of which have appeared in many exhibitions.

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MYCOLOGY

THE HIDDEN LIFE OF TRUFFLES

Not just for gourmands, truffles play essential roles in the health of ecosystems

By James M. Trappe and Andrew W. Claridge

IT'S A COOL NOVEMBER DAY NEAR BOLOGNA, ITALY. WE ARE STROLLING THROUGH THE WOODS WITH truffle hunter Mirko Illice and his little dog, Clinto. Clinto runs back and forth among the oak trees sniffing the ground, pausing, and then running again. Suddenly, he stops and digs furiously with both paws. "Ah, he's found an Italian white truffle," Mirko explains. "He uses both paws only when he finds one of those." Mirko gently pulls the excited dog from the spot and pushes through the soil with his fingers. He extracts a yellowish brown lump the size of a golf ball and sniffs it. "*Benissimo,* Clinto," Mirko intones. Though not the finest example of the species, *Tuber magnatum*—which grows only in northern Italy, Serbia and Croatia—Clinto's find will fetch a nice price of about $100 at the Saturday market.

Throughout history, truffles have appeared on the menu and in folklore. The Pharaoh Khufu served them at his royal table. Bedouins, Kalahari Bushmen and Australian Aborigines have hunted them for countless generations in deserts. The Romans savored them and thought they were produced by thunder. Epicures today who prize truffles' earthy aroma and flavors are willing to pay steep prices at the market—the Italian white species has fetched more than $3,000 per kilogram.

Despite humanity's abiding interest in truffles, much about their biology has remained veiled in mystery. Over the past four decades, however, genetic analyses and field experiments have clarified the origins and functions of these organisms. These studies have revealed that truffles play crucial ecological roles in many ecosystems. The findings are informing strategies for conserving some endangered species that rely on these denizens of the underworld.

A FUNGUS AMONG US

TRUFFLES, LIKE MUSHROOMS, are the fruit of fungi. These fleshy organs are temporary reproductive structures that produce spores, which eventually germinate and give rise to new offspring. What sets truffles apart from mushrooms is that their spore-laden fruit forms below the ground

IN BRIEF

The truffles that appear on restaurant menus and on the shelves of luxury food purveyors represent only a small fraction of the world's truffle species. **Truffles figure** importantly in ecosystems, sustaining both plants and animals. **Recognition** of the ecological significance of truffles is aiding efforts to conserve threatened species that depend on them. **One popular variety** of truffle has been successfully cultivated, but agriculture has yet to tame other prized species.

JOERG LEHMANN *Getty Images*

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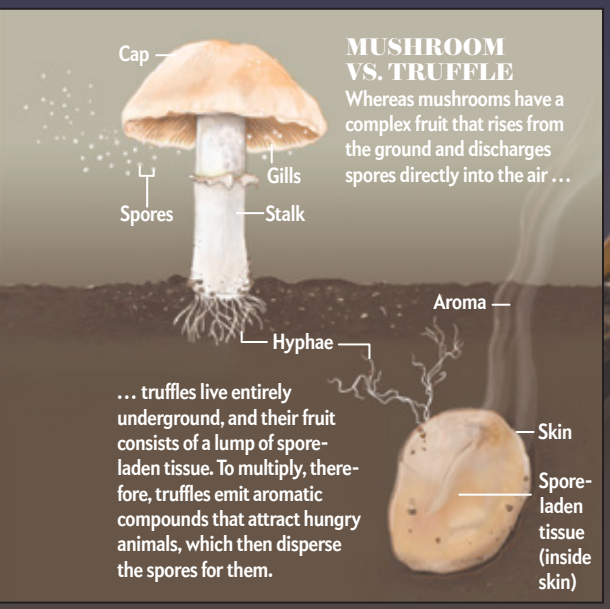
ECOLOGICAL SIGNIFICANCE

Fundamental Fungus

Truffles figure importantly in many ecosystems, benefiting both plants and animals. In the forests of the Pacific Northwest, for example, *Rhizopogon* truffles help Douglas-fir trees to obtain the water and nutrients they need. They also serve as a key source of food for the northern flying squirrel, which in turn is a favorite prey species of the endangered northern spotted owl. Protecting the owl's habitat, then, requires ensuring conditions favorable to truffles.

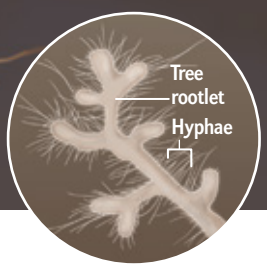


MUSHROOM VS. TRUFFLE

Whereas mushrooms have a complex fruit that rises from the ground and discharges spores directly into the air … … truffles live entirely underground, and their fruit consists of a lump of spore-laden tissue. To multiply, therefore, truffles emit aromatic compounds that attract hungry animals, which then disperse the spores for them.

TWO-WAY STREET

Truffles form symbiotic relationships with plants by way of a network of microfibers called hyphae that grow among plant rootlets to form a shared organ called an ectomycorrhiza that enables each partner to provide the other with nutrients it cannot obtain for itself.



rather than above. Technically, true truffles are those multicellular fungi that belong to the Ascomycota phylum of organisms and are marketed as food. But there are "false truffles" in the fungal phylum Basidiomycota that function like true truffles. In view of these similarities, we refer to all fleshy fungi that fruit underground as truffles.

Scientific efforts to expose the secrets of truffles date to the 1800s, when would-be truffle growers in Germany asked a botanist, Albert Bernhard Frank, to figure out how the delicacies propagate. Frank's studies revealed that the fungi grow on and into the tiny feeder rootlets that trees use to absorb water and nutrients from the earth. On the basis of those observations, he proposed that the organisms have a symbiotic relationship in which each provides nutrients to the other. He further posited that such relationships between subterranean fungi and plants are widespread and that they shape the growth and health of many plant communities. Frank's theories contradicted conventional wisdom about truffles and other fungi—namely that they all brought about disease and rot in plants—and drew considerable opposition from his peers. Nearly a century later scholars finally had definitive evidence, which showed that Frank got the story right.

All truffles and mushrooms produce networks of filaments, or hyphae, that grow among plant rootlets to form a shared absorptive organ known as a mycorrhiza. Thus joined, the fungus provides the plant with precious nutrients and water, its tiny hyphae able to reach into pockets of soil inaccessible to the plant's much larger roots. The plant, in turn, furnishes its consort with sugars and other nutrients that it generates through photosynthesis—products that the fungus needs but cannot produce on its own because it does not photosynthesize. So beneficial is this partnership that nearly all trees and other woody plants require it for survival, as do the associated fungi. Most herbaceous plants (those that do not have a permanent woody stem aboveground) form mycorrhizae, too, albeit with different fungi.

Many fungal species, including all the ones that yield truffles, form a variant of the mycorrhiza called an ectomycorrhiza, in which the fungus envelops the feeder rootlets with a protective outer tissue. The diversity of these ectomycorrhizal fungi is impressive: one of us (Trappe) estimates that some 2,000 species are associated with the Douglas fir (an evergreen used for timber and Christmas trees), and probably as many or more fungal species partner only with Australia's eucalyptus

LUCY READING-IKKANDA

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trees. Numerous other commercially and ecologically important tree species also rely on ectomycorrhizal fungi. Most of these fungi fruit aboveground as mushrooms, but several thousand species produce truffles.

GOING UNDER

COMPARISONS of the morphology and gene sequences of truffle and mushroom species indicate that most truffles have evolved from mushrooms. But given that truffles require aboveground dispersal of their spores to propagate, why would natural selection favor the evolution of species that hide underground? Consider the reproductive tactic of mushrooms. Although mushrooms exhibit a multitude of structures and colors, they all have fruiting bodies that can discharge spores directly into the air. The airborne spores may then alight nearby or far away to germinate and potentially establish a new colony in association with the roots of a compatible plant host. It is a highly effective approach.

The mushroom strategy is not foolproof, however. Most mushrooms have little defense against environmental hazards such as heat, drying winds, frost and grazing animals. Every day a few spores mature and are discharged. But if inclement weather dries or freezes a mushroom, spore production usually grinds to a halt.

Where such hazards are commonplace, new evolutionary adaptations have arisen. The most successful alternative has been for the fungus to fruit underground. Once the soil is wet enough for the subterranean fruiting body to form, it is insulated from vagaries of weather. The truffle develops with relative impunity, continuing to produce and nurture its spores even when aboveground conditions become intolerable to mushrooms.

At first glance, the truffle's solution might seem facile. Truffles are visibly less complex in shape than mushrooms are. No longer does the fungus need to expend the energy required to push its spore-bearing tissues aboveground on a stalk or develop a cap or other structure for producing and releasing the spores. The truffle is but a lump of spore-bearing tissue, usually enclosed by a protective skin.

The problem is that the truffles cannot themselves liberate their spores, trapped as they are in their underground realm. That feat demands an alternative dispersal system. And therein lies the complexity of the truffle's scheme. Over millions of years, as truffles retreated underground, mutations eventually led to the formation of aromatic compounds attractive to animals. Each truffle species has its own array of aromatics that are largely absent in immature specimens but intensify and emerge as the spores mature.

Of the thousands of kinds of truffles that exist today, only a few dozen appeal to humans. The rest are too small or too tough, or they possess aromas that are unremarkable or downright repugnant. To other animals, however, they are irresistible, their olfactory charms wafting up from the soil. Small mammals such as mice, squirrels and rabbits in the Northern Hemisphere and rat-kangaroos, armadillos and meerkats in the Southern Hemisphere are the main truffle gourmands. But their larger counterparts—deer, bears, baboons and wallabies, among others—also seek out the undercover fungi. Mollusks are attracted to truffles, too. And insects may feed on truffles or lay eggs in them so that their larvae have a ready food source when they hatch.

When an animal eats a truffle, most of the flesh is digested, but the spores pass through unharmed and are defecated on the ground, where they can germinate if the conditions are right. This dispersal system has advantages over the one that mushrooms employ. Feces concentrate spores, in contrast to the more diffuse scattering that occurs with aerial dissemination. In addition, feces are more likely to be deposited in the same kinds of areas where the animals forage for truffles, as opposed to the more random transport of airborne spores. This similarity of environment is beneficial because it increases the likelihood that the spores will land in a spot that has an appropriate plant species with which to establish a mycorrhiza.

Not all truffles rely on scent to attract animals, however. In New Zealand, which lacks native terrestrial mammals, some truffles have evolved rainbow hues that mimic the colors of fruits prized by the local birds. The *Paurocotylis pila* truffle, for one, emerges from the ground as it expands and lies on the forest floor, resembling the plump, red berrylike base of the seeds of *Podocarpus* trees that are a favorite bird food. (Although these colorful fungi do poke above the ground, they are nonetheless considered truffles because their spore-bearing tissues are enclosed in

DEPENDENTS

Truffle Eaters

The animals below are among the many that dine on truffles.

DAVE WATTS *Alamy (long-footed potoroo)*; MILLARD H. SHARP *Science Source (meerkat)*; GETTY IMAGES *(kiwi)*; NIGEL J. DENNIS *Science Source (baboon)*; GREGORY OCHOCKI *Science Source (bear)*

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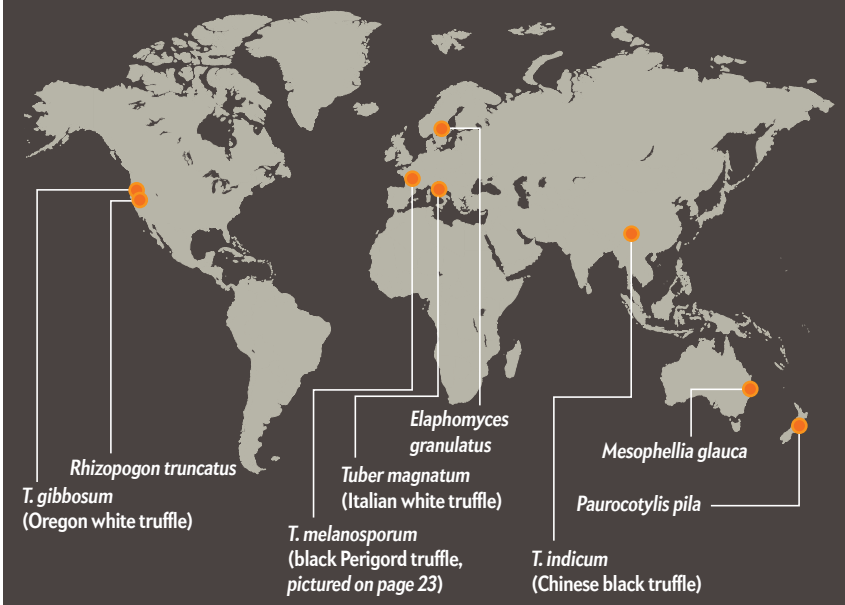
GLOBAL DIVERSITY

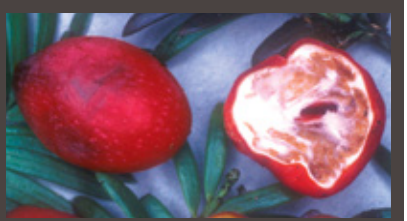
Where Truffles Grow

Truffle species number in the thousands; the map shows representative locations where those mentioned in this article grow wild. The highest-known diversity of species occurs in Mediterranean Europe, western North America and Australia—regions mostly characterized by cool, rainy winters and warm, dry summers. With their subterranean lifestyle, truffles are protected from the heat, drought and frost that can occur when the fungi produce their fruit.



M. glauca

R. truncatus


P. pila

LUCY READING-IKKANDA (*map*); COURTESY OF JAMES M. TRAPPE (*M. glauca*); COURTESY OF MATT TRAPPE (*R. truncatus*); COURTESY OF MICHAEL CASTELLANO AND JAMES M. TRAPPE (*P. pila*)

THE SCIENCE OF FOOD

a skin, and they thus depend on animals to disperse their spores.)

Yet another dispersal mechanism has evolved with a few groups of truffles, notably members of the ubiquitous Elaphomycetaceae family and the Mesophelliaceae family, which is endemic to Australasia. Their spores mature into a powder rather than a fleshy, spore-bearing tissue. The powder of *Elaphomyces granulatus,* for instance, is enclosed in a thick rind that is eaten by the animal, freeing the spores. Some of the Mesophelliaceae have a similar structure; others, such as *Mesophellia glauca,* possess a powdery spore mass sandwiched between a thin, hard outer rind and an edible inner core.

Even the spores of uneaten truffles can wander. After maturing, truffles decay into a slimy, larva-infested suspension in the soil. Invertebrates feed on this rotting tissue or move through it, picking up spores along the way. Truffle spores also travel when predators capture a small truffle-eating species: owls and hawks may carry rodents full of truffles considerable distances to their nests or roosts, where they eat the prey whole or eviscerate and discard the entrails. Either way the spores return to the soil, where they may give rise to new truffles.

TOGETHER FOREVER

EVOLUTION'S EXPERIMENTS with truffles have been remarkably similar in both the Northern and Southern Hemispheres, despite taking place long after the continents separated. The host plants in these regions are entirely different: whereas pines, beeches and oaks, for instance, partner with truffles in the north, eucalyptus and southern beeches play that role in the south. The truffle and animal species are likewise distinct between hemispheres. Yet the ecosystems and their components—the trees, truffles and animals—function in much the same way.

The greatest known diversity of truffles occurs in temperate areas of Mediterranean Europe, western North America and Australia (although most of Asia, Africa and South America remain unexplored by truffle researchers). These areas have climates with cool, rainy winters and warm, dry summers. Their fungal fruiting seasons are usually spring and autumn, when weather tends to be erratic: some years bring warm, dry spells and others deliver frost; both conditions are inimical to mushrooms. Over time, then, natural selection favored those fungi that sought refuge underground in these regions.

Exactly when the first truffles evolved is uncertain, but scientists have unearthed some clues to their origins. The oldest fossil ectomycorrhizae on record date to around 50 million years ago. And the ancestors of today's pines and other trees with which truffles form essential relationships arose some 85 million years ago. We can assume, then, that truffles emerged sometime between 85 million and 50 million years ago.

Given this long-standing association between truffles and plants, it is no surprise that the fungi figure importantly in the ecology of many habitats. Not only are they essential to the functioning of numerous plant species, but animals have come to rely on them for food. In the U.S. at least one creature, the Western red-

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backed vole, depends almost entirely on truffles for sustenance. And the northern flying squirrel, found in North America, eats mostly truffles when available in the wild. On the other side of the globe, in Australia, a marsupial known as the long-footed potoroo subsists on a diet that is about 95 percent truffles. Its fellow marsupials—the other rat-kangaroos and bandicoots—also bank heavily on truffles. And many other creatures the world over routinely supplement their primary food sources with these fungi.

Scientists' developing knowledge of the intimate relationship among truffles, their plant hosts and their animal carriers is guiding the efforts of cultivators and conservationists alike. In the 1980s in Oregon, Mike Castellano of the U.S. Forest Service, Mike Amaranthus of Mycorrhizal Applications and their colleagues began outfitting nursery seedlings with spores of hearty *Rhizopogon* truffle species to help the seedlings withstand drought and other stressful conditions in plantations. Going forward, cultivators could conceivably augment their returns if they substituted gourmet truffles for *Rhizopogon*. For example, Christmas tree farms in the Pacific Northwest could additionally produce the delicious Oregon white truffle, *Tuber gibbosum*. Thus far, however, attempts to inoculate trees with this truffle species have produced inconsistent results.

Meanwhile one of us (Claridge) has used truffles to help determine the population sizes of endangered animals in southeastern Australia—a prerequisite to developing effective protection or recovery programs for these species. He soaked foam pads in olive oil infused with aromatics of the European black Perigord truffle (a favorite of humans) to attract potoroos and other truffle-loving marsupials to stations where they were photographed by motion-sensing digital cameras. The approach detected about 50 times as many of these creatures as had been counted by the traditional method of cage trapping. If the success rates were this high with imported truffle oil, which he used because it was readily available for purchase, what might the figures be once the odors of native Australian truffles are put to the test? That question remains to be answered.

To protect endangered animals that regularly eat truffles, conservationists will have to ensure the availability of their food. This provision applies not only to those animals that depend directly on truffles but also to their predators. Thus, restoring the habitat of the threatened northern spotted owl in the Pacific Northwest requires meeting the needs of the owl's primary prey, the northern flying squirrel, which eats mostly truffles.

FAST FACTS

A Fruit of the Earth

Black Perigord truffles contain androstenol, a sex hormone found in hog saliva. Humans also produce the compound in their sweat glands.

Truffle hunters have long used female pigs to locate the fungi underground, but increasingly they are turning to dogs for assistance because the dogs are more willing than the pigs to accept an alternative food reward for their efforts.

Most commercially available truffle oils are flavored synthetically with laboratory-made compounds such as 2,4-dithiapentane, one of many molecules that give Italian white truffles their distinctive aroma.

Some truffles contain compounds that have potent antituberculosis effects; others exhibit strong anti-inflammatory and antioxidant properties.

TAMING THE TRUFFLE

ALTHOUGH RESEARCHERS have learned much about the ecology of truffles in recent decades, the science of growing them has changed little since the 1960s, when French scientists developed a greenhouse technique for adding spores of the black Perigord truffle into the potting mix of oak and hazel seedlings that are later planted in suitable sites to form truffle orchards, or *truffières*. Under ideal growing conditions, the *truffières* can produce a marketable crop in four to five years.

After many failed attempts, similar *truffières* were finally established in the U.S. in the 1980s. Today the most productive truffle grower in North America is Tennessee Truffle, founded by Tom Michaels, who studied with Trappe as a graduate student. Michaels's *truffière* has produced up to 100 kilograms a year of black Perigord truffles since 2008. To get these results, he pays careful attention to the soil, adding lime every year to keep it alkaline and high in calcium. Australia, New Zealand and Argentina now produce Perigord truffles as well.

In stark contrast to the triumphs of Perigord truffle farming, efforts to cultivate the most highly prized truffle species—the Italian white truffle that Mirko and Clinto were hunting, which has an especially intense aroma—have failed. For reasons unknown, this species so far refuses to produce truffles in *truffières*. Sequencing of the complete genome of this king of truffles may yield clues on how to surmount the barrier to producing it on command.

Concurrently, truffles may become more prevalent even without cultivation: as the earth warms, the hotter, drier habitats that many truffles favor will spread, setting the stage for increased production and accelerated evolution. Climate change, then, may yield a benefit for some: more truffles for men and beasts. SA

James M. Trappe is scientist emeritus at the U.S. Forest Service and a professor of forest science at Oregon State University. He has discovered more than 200 new truffle species on five continents. Jim wonders why anyone would go fishing instead of seeking new truffles. **Andrew W. Claridge** is a senior research scientist with the New South Wales Office of Environment and Heritage and a visiting fellow at the University of New South Wales in Australia. He has studied for more than 20 years interrelationships among mammals and the fungi they eat. His favorite hobby is fishing.

MORE TO EXPLORE

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SUSTAINABLE AGRICULTURE

THE FUTURE OF CHOCOLATE

Researchers are racing to fortify the embattled cacao tree and to meet increasing demand for cocoa made from its seeds

By Harold Schmitz and Howard-Yana Shapiro

Photograph by Adam Voorhes

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TO THE ANCIENT MAYANS, IT WAS THE FOOD OF THE GODS. NINETEENTH-CENTURY CUBANS used it as an aphrodisiac. In the 20th century, American culinary authority Fannie Farmer recommended its "stimulating effect" for "cases of enfeebled digestion." Throughout history people have prized cocoa—the defining ingredient of chocolate—a tradition that endures in our modern era. This past Valentine's Day alone, Americans dropped an estimated $1.7 billion on chocolate. Around the world people spend more than $98 billion a year on the treat. And with appetite on the rise thanks to expanding population size and growing numbers of people in the developing world who can afford chocolate, demand may outstrip supply in the near future.

All this cocoa production does more than feed our collective sweet tooth: the five million to six million farmers in the tropics who cultivate the cacao trees from which cocoa is produced rely on the sales of the seeds to feed themselves and their families. Workers extract the seeds (often called beans) from football-shaped pods and then ferment and dry them to form cocoa liquor, butter and powder. Roughly 50 million livelihoods depend on the long production road the cacao seeds travel from farm to candy on store shelves. In Ivory Coast, source of 40 percent of the world's cocoa, such farming accounts for a full 15 percent of GDP and employs 5 percent of households.

"Many of these farmers use their cacao trees like ATM machines. They pick some pods and sell them to quickly raise cash for school fees or medical expenses. The trees play an absolutely critical role in rural life," observes Peter Läderach of the International Center for Tropical Agriculture, who has led research into the effects of climate change on cacao farming in Ivory Coast and Ghana. Along with Nigeria and Cameroon, those countries produce 70 percent of the world's cocoa supply.

But the delicate "chocolate tree," *Theobroma cacao,* is in peril. The tree has always been extremely susceptible to pests and fungal infections. In 1988, just six years after Mars, Incorporated (our employer), established its Center for Cocoa Science in the thriving cacao-growing region of Bahia, Brazil, the fungal disease witches' broom was found in the area. It reduced production by 80 percent, driving people whose families had grown cacao for generations to abandon their farms and move to city shantytowns—effectively destroying in a few short years a vast archive of cacao-farming knowledge built over centuries. Now another fungal disease, frosty pod rot, has spread throughout Latin America and may soon arrive in Brazil, where it could be even more devastating than witches' broom. And what would happen if witches' broom were introduced into West Africa, either by accident or in an act of bioterrorism?

Making matters worse, many farmers, particularly those in Africa, struggle to obtain the best seeds, fertilizers and fungicides, as well as training in their use. Yields—and the income they generate—are thus a third or less of their potential. Meanwhile the world clamors for more cocoa: manufacturers reckon the industry now produces around 4.4 million metric tons of cocoa; by 2020 they expect that demand will outstrip supply by one million metric tons.

In view of the challenges, we and others in the chocolate industry worry that without fast action on a number of fronts, cacao farming could slide into a downward spiral. To that end, researchers are currently working to find ways to multiply yields sustainably. Some of the efforts involve nontraditional collaboration among farmers, corporations, universities and government agencies, including the U.S. Department of Agriculture. One such collaboration, led by Mars, has sequenced the cacao genome in an attempt to find ways to breed hardier trees. Whether these efforts will succeed in raising yields enough to save the livelihoods of farmers and meet the world's passion for choco-

IN BRIEF

Consumer demand for chocolate is on the rise. But the cacao tree—the seeds of which yield cocoa powder—is threatened by pests, fungal infections, climate change and farmers' lack of access to yield-enhancing fertilizers.

Researchers are working on multiple approaches that could bolster the fragile tree. Selective breeding and farmer education efforts are under way, as is work to develop novel planting, irrigation and pest-management techniques.

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Black pod fungus infects the seed pods of a cacao tree in the Philippines (*above*). Planting cacao with other crops, such as coconut in Brazil, provides year-round income and food and increases the water-holding capacity of the crops (*left*).

late remains to be determined, but we see some encouraging signs.

THE ASSAULT ON COCOA

CACAO FARMERS CERTAINLY FEEL the pressure to increase yields, but the crop is hard to grow. The cacao tree originated in the upper Amazon, in what is now Ecuador, and was imported into the Mexican empire of the Olmec, who domesticated it and then sent it to the Mayans and Aztecs. Portuguese and Spanish sailors took the tree to colonies in Africa and Asia. Today the cacao tree still grows only in a narrow band within about 18 degrees north and south of the equator. It prefers rich, well-drained soils, which are often scarce in the tropics. And it requires heat and humidity, which lead to fungal, viral and pest problems that claim up to 40 percent of the crop. Besides witches' broom and frosty pod rot in the Americas, other threats to the tree include cocoa swollen shoot virus in West Africa and a moth called the cocoa pod borer in Southeast Asia, the latter often costing $600 million in crop losses a year. Ghana's cacao trees suffer insect damage, black pod rot, water mold and the swollen shoot virus. Experts fear that these scourges are now attacking the healthier trees in neighboring Ivory Coast. We worry that Africa or Asia could suffer a Brazil-like collapse because of these threats.

The limited genetic variation of the tree does not help matters. Mars cacao geneticist Juan Carlos Motamayor and his collaborators found through genetic tracing that cacao comes in 10 different major varieties, all of which belong to the same single species. Thus, although the similarity among strains means that growers can crossbreed them easily, it also means that the collected strains do not contain enough variation to provide much natural resilience to pests and disease; if one strain is genetically susceptible, chances are good they all will succumb. When farmers save their own seeds to plant new trees, this local inbreeding leaves the trees even more susceptible to pests and fungi.

Beyond the usual difficulties, growing conditions seem to be getting worse. Weather extremes such as floods, droughts and windstorms have always made farming in the tropics difficult. Climate change is beginning to intensify these extremes, which could worsen pest and disease infestation and disrupt water supplies. The 2007 report of the Intergovernmental Panel on Climate Change predicted that by 2020 yields in Africa from rain-fed crops—which make up the vast majority of African crops, including cacao—could be reduced by up to 50 percent in some countries. The same report predicted increases in temperature and associated decreases in freshwater in Amazonia by midcentury. Furthermore, Läderach's research on the effects of climate change in Ghana and Ivory Coast predicts that the ideal cacao-growing areas will shift to higher altitudes to compensate for rising temperatures. "The problem is that much of West Africa is relatively flat, and there is no 'uphill,'" he commented in a September 2011 press release. Climate shifts could thus lead to drastic decreases in terrain suitable for cacao crops. In Indonesia, meanwhile, the annual monsoon rains are becoming more intense over shorter periods, often knocking the flowers off the cacao trees, thereby preventing pod formation.

Poverty exacerbates these challenges. In Ivory Coast and Ghana, internal movement of people of various ethnic origins and immigration from poorer, neighboring Burkina Faso have not only created tensions between richer and poorer people but also muddied property rights. In both countries, farmers hesitate to invest in trees that their children may not inherit, and many do not want to continue cacao farming unless tree productivity can be significantly improved. Young people

COURTESY OF MARS, INCORPORATED

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are moving out of the cacao-growing areas, which translates to an increase in the average age of farmers and a decrease in their education levels.

Unfortunately, fertilizers, fungicides and pesticides—the most effective ways to significantly boost crop production—are rarely used in the region because farmers cannot afford them and do not know how to employ them effectively. Even if they could afford these tools, the remote locations of the farms, which are often accessible only via poorly maintained roads, mean governments and merchants have a hard time delivering these products to farmers and providing education on how best to use them.

SAVING CHOCOLATE

BECAUSE THE THREATS to cocoa production come from pests, disease, climate change and poverty, work must be done on all these issues to raise yields without tearing down rain forests to gain arable land. Abandoned land must be rehabilitated by enriching the soil with fertilizer and by planting trees and shrubs to control erosion. Whereas the average global yield is about 460 kilograms of cacao beans per hectare, crops tended using modern farming techniques could easily yield 1,500 kilograms or more per hectare. For many cacao farmers in developing nations, tripling their yields would mean the difference between a subsistence-level income of $1 a day and a manageable $3 a day.

Science took a critical step toward raising yields about five years ago, when researchers from Mars, the USDA's Agricultural Research Service (ARS), IBM and other institutions sequenced and analyzed the genome of the so-called Matina 1-6 variety of *T. cacao,* which many experts consider to be the progenitor of 96 percent or more of all the cacao grown in the world. We then made the results freely available to all—including Mars's competitors—over the Internet because we felt no single organization has the resources to, in a timely manner, do the breeding work needed to save the species from the various crises it faces. Cacao has not received

REGIONAL VARIATION

Global Efforts to Boost Cacao Crops

Cacao trees grow only in a slim band within 18 degrees north and south of the equator. The threats to cacao crops vary from region to region. Below are representative problems and possible solutions for imperiled cacao crops across the tropics.

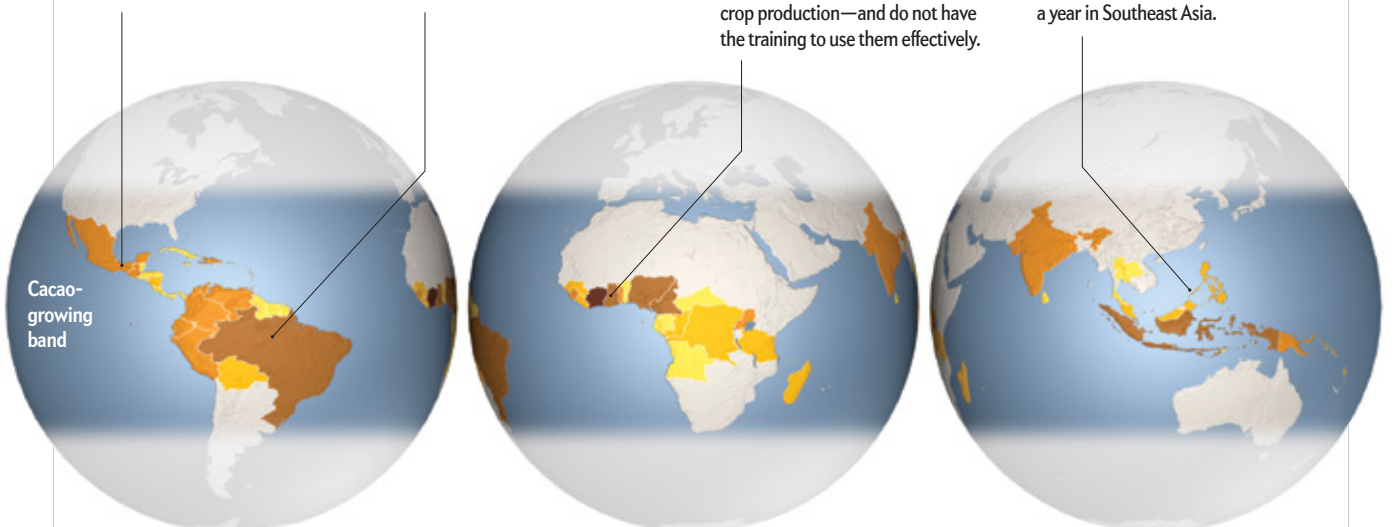
Threats

Frosty pod rot, a fungal disease that attacks cacao pods, has spread across Latin America and may soon enter Brazil.

Unreliable rainfall in Brazil could worsen in the face of climate change, subjecting cacao crops to damaging water shortages.

Poverty in Ghana and other parts of West Africa means that farmers cannot afford fertilizers, fungicides and pesticides—which could boost crop production—and do not have the training to use them effectively.

Cocoa pod borer, a moth whose larvae feed inside cacao pods and damage the seeds, can cause hundreds of millions of dollars in crop losses a year in Southeast Asia.



Solutions

Breed hardier trees. Using the cacao genome map, researchers have identified a gene variant that confers resistance to frosty pod rot. Farmers are grafting branches from resistant cultivars onto their trees.

Develop mixed agroforestry systems. Planting cacao trees among food crops, timber trees and fodder trees improves water-holding capacity throughout the system by varying the root structures in the tree matrix.

Help farmers help themselves. The Cocoa Livelihoods Program has been working to educate farmers, promote crop diversification and improve the efficiency of supply chains.

Develop strategies for integrated pest management. Some farmers are no longer relying solely on pesticides that can harm local biodiversity and are, for example, using natural foes of the pod borer to help control it.

2013 Cocoa Production (metric tons, estimated) <2,000 2,000+ 10,000+ 250,000+ 1,000,000+

SOURCE: UNITED NATIONS FOOD AND AGRICULTURE ORGANIZATION (*cacao production in 2013*)

Graphic by George Retseck

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the genetic attention paid to commodities such as rice, corn and wheat—attention that has dramatically improved yields for these crops. (Another consortium, led by the French agricultural research organization CIRAD, announced its sequencing of a different variety of cacao shortly after we released our sequence.)

To be effective, the molecular research on cacao taking place in labs in the developed world has to connect to what breeders are doing on the ground in the developing world. Mars and the ARS have thus, over the past decade, organized networks of cacao breeders in West Africa, Southeast Asia and Latin America. The breeders are using the cacao genome to discover where, among the world's cacao crops, disease resistance, enhanced yields, water and nutrient use efficiency, and climate change adaptability are to be found.

Thanks to such collaborations, when Wilbert Phillips-Mora, a breeder in Costa Rica, found a cultivar that exhibited some resistance to frosty pod rot, he sent samples to the molecular biologists in the network, who were then able to use the genome map to identify the gene variant in the cultivar that confers resistance to the dread fungus. In subsequent breeding efforts, the breeders can quickly determine if new cultivars carry that trait or other useful traits for the next generation of cacao trees. Already farmers in Latin America are grafting parts of branches from these new plants to their trees.

Breeders have previously identified cultivars that resist witches' broom, but they do not produce high-quality cocoa. The new breeding work raises the prospect of mixing such desired attributes as resistance and quality in a single *T. cacao* cultivar through careful crossbreeding. In a similar vein, researchers have discovered a type of cacao resistant to Southeast Asia's vascular-streak dieback disease and are currently analyzing the genetic underpinnings of that trait. Cacao experts ultimately hope to breed trees that are resistant to other fungi and pests and that can endure the heat and water scarcity that often accompany climate change while preserving the quality of the cocoa beans.

Researchers also aim to produce shorter trees. During harvest, farmers cut the cacao pods from the tree with knives on the ends of long poles. They take great care to not damage the site of pod growth. A shorter but equally or more productive tree would require fewer resources to generate the pods and be easier to harvest.

Yet even short, drought-tolerant trees still need some water. Eventually, no matter how efficient our cultivars, cacao growers will have to figure out how to irrigate more crops instead of relying on fickle rainfall. Farmers, scientists, aid agencies and foundations are trying different approaches to solving this problem across regions. Brazil is working on two radically different strategies. In the first, small farmers are trained to develop mixed agroforestry systems, in which cacao trees are planted among food crops, fodder trees and timber trees. These mixes improve water-holding capacity throughout the entire system by varying the root structures throughout the matrix of trees. The second strategy takes the opposite tack, creating large plantations of cacao trees in Bahia, Brazil, at higher altitude—out of the traditional pest and disease ranges—in the full sun and irrigating them with fertilizer-enriched water for maximum productivity. Vietnamese growers—some of whom are encountering falling water levels as a result of unsustainable groundwater use—are making reservoirs to collect rainwater for irrigating the cacao trees.

As is the case for water supplies, each cacao-growing region of the world has its own set of challenges and organizations that are stepping up to tackle them. In early 2009 the World Cocoa Foundation (WCF) began a $40-million program, funded by the Bill & Melinda Gates Foundation and 17 companies, to improve the livelihoods of cacao farmers in five West and Central African countries. By 2014 the Cocoa Livelihoods Program had trained nearly 200,000 farmers, working with them to enhance productivity and quality, promote crop diversification and boost supply-chain efficiency.

The program is based on a successful series of WCF field schools for African cacao farmers, themselves modeled on similar United Nations Food and Agriculture Organization farmer field schools. School facilitators found local farmer leaders to do much of the teaching, and aside from covering obvious topics such as disease management, pruning and harvesting, the schools tackled topics such as malaria, HIV/AIDS, farm safety and the avoidance of child labor. According to WCF president Bill Guyton, graduates increased their incomes by 23 to 55 percent.

In Southeast Asia, farmers tend to get the training they need because of better extension services. The main hurdle there is to develop integrated pest-management techniques to deal with the devastating pod borer—work that has begun but still has a long way to go. Such techniques include using pheromone-based traps and black ants (natural enemies of the pod borer) to control the moths and not relying solely on pesticides, which could damage the biodiversity in the region.

Tripling cacao yields sustainably is perfectly possible. Effective fertilizers, fungicides and training programs already exist, and scientists are beginning to develop cultivars resistant to some of the problems that have long dogged the cacao tree. But getting all these resources to poor, remote farmers so that they can become better off and better connected is a job too big for any single government, U.N. agency, company or project. Meeting that objective will take innovative, energetic coalitions. We are optimistic that a more secure future for chocolate and the vast social, cultural and ecological ecosystem it supports will come to pass, but it must be said that making cacao a truly sustainable crop will be a grand challenge indeed. SA

Harold Schmitz is chief science officer of Mars, Incorporated. A food scientist by training, Schmitz focuses on the food-production supply chain and its influence on human and animal health and on ecological, environmental, social and cultural sustainability. He serves on the executive committee of the Government-University-Industry Research Roundtable at the National Academies. **Howard-Yana Shapiro** is chief agricultural officer and Mars Advanced Research Institute Fellow at Mars. He led the global effort to sequence the genome of the cacao tree.

MORE TO EXPLORE

Chocolate: History, Culture, and Heritage. Edited by Louis Evan Grivetti and Howard-Yana Shapiro. Wiley, 2009.
The Future of Chocolate on Earth. Video by Distinctive Voices: www.youtube.com/watch?v=2BvTw5LtCis
Cacao Genome Database. A public and private collaboration: www.cacaogenomedb.org
Sustainable Cocoa Initiative: Securing Cocoa's Future: www.mars.com/cocoasustainability/home.aspx

scientificamerican.com/magazine/sa

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Dinner is served: Asian shore crabs have spread rapidly since their introduction on the U.S. East Coast nearly three decades ago. Here they are served on a "plate" of invasive wakame seaweed.

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CULINARY ECOLOGY

HOW (AND WHY) TO EAT INVASIVE SPECIES

What's the best way to control ecological pests? Feed them to the world's greatest predator—us

By Bun Lai

IN BRIEF

Introduced pest species wreak about $120 billion a year in economic damage in the U.S. alone. These alien species often invade ecosystems unchecked because they lack natural predators.

Humans are omnivores, however, and many people enjoy adding new foods to their diet. From our spot at the top of the food chain, we could combat the spread of invasive species by eating them.

Eating sea squirts, locust, earthworms, and jellyfish requires a spirit of adventure and an open mind. Chefs can help smooth the process by producing recipes that turn pests into delicious dishes.

The recipes here are just a few of those that have appeared on the menu at restaurants around the world where chefs are protecting local ecosystems by creating a market for invasive species.

Photograph by Grant Cornett

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MY RESTAURANT, CALLED Miya's Sushi, is just a few miles from Long Island Sound in New Haven, Conn. We have made it our goal to return our cuisine to the roots of sushi, meaning simply to use what we have available where we live. Too often what we find now are invasive species—unwanted plants and animals humans have introduced to ecosystems. Nationwide, invasive species such as the wild boar and Asian carp are destroying farms and fisheries, causing economic damage that has been estimated at $120 billion a year.

Our solution? Eat them. By collecting invasive seafood on shellfish beds, for instance, we basically provide a free weeding service. I also hope to convince the world that these invasives can be delicious, if you get into the right mind-set.

Consider the stalked tunicate—also known by the delicious-sounding name "Asian sea squirt"—which has taken over what used to be blue mussel habitat from Maine to New Jersey. The alien sea squirt, which is indigenous to the Philippines, is considered a fouling organism and a pest by the shellfish industry. In South Korea, however, it is considered a delicacy and even an aphrodisiac.

I first ate sea squirt at a Korean sushi bar in New York City. The saclike squirts were arranged like a sunflower in the middle of a bright orange plate. As I bit into one of the yellow appendages, it burst with salty, viscous, warm liquid. Although I could not see the liquid, I could taste its phlegmy consistency, and it took all my willpower to keep it in my mouth and even more effort to swallow it.

Buckminster Fuller used to say that one should "dare to be naive." I think it takes a bit of his approach to truly accept new ways of doing things—including, of course, eating. The next time I tried sea squirt, I scraped one off a pier. I sliced open its tough outer membrane, which revealed a soft, orange flesh, like mango. With barely a pause, I slurped it into my mouth from the palm of my hand. This time it was good.

I have foraged, fished and hunted many different species of plants and animals; the following are just a few of the dishes I have served in my restaurant from the invasive ones. SA

Bun Lai, a 2013 James Beard Award–nominated chef, dives and fishes in Long Island Sound to supply his restaurant with underutilized seafood.

MORE TO EXPLORE

Eat the Invaders: www.eattheinvaders.org
National Invasive Species Information Center: www.invasivespeciesinfo.gov

scientificamerican.com/magazine/sa

THE SCIENCE OF FOOD

TODAY'S SPECIALS

La Soupe des Mean Greenies

European green crabs made their way to the U.S. in the 19th century. They voraciously consume the larvae of commercial shellfish species and are considered one of the top 100 most destructive invasive species in the world. I smoke the crabs with applewood, dehydrate them with lemongrass and hot peppers, then pulverize them into a powder that I use for the base of a savory crab-miso soup. I then steam whole crabs in a hoppy beer and hot Ethiopian spices and serve them atop the soup as if they are struggling to climb out—a symbol of the tenacity of invasive species.

Stone Soup

The European flat oyster was deliberately introduced to Maine in the 1940s and competes with native shellfish. I simmer a rock covered in European flat oysters, rockweed and invasive wakame (sea mustard) in a sake broth flavored with Queen Anne's lace root, wild onions and native morels. I serve the soup in a large iron pot—enough for a small village to share.

Forest Fritters

Invasive earthworms have spread to every continent and oceanic island in the world. European settlers introduced one third of all the species of earthworms that inhabit North America. Although native earthworms are beneficial, invasive ones can drastically alter the biodiversity of a forest and lower its resistance to other invasive species. Earthworms are much higher in protein than steak, and they contain many important nutrients. To make a worm safe and pleasant to eat, one must first squeeze the dirt out of its gut and then cook it to kill any harmful soil microbes or parasites remaining. I butterfly cleaned worms, rinse them and then chop them before cooking.

My recipe for earthworms is inspired by fritters that the Vietnamese make from freshwater worms. I season chopped earthworms with ginger, scallions, hot peppers, grated orange peels and lemongrass. Then I fry them into fritters, which look more appealing than whole worms do. Prepared this way, worms actually have a pleasant mouth-feel similar to ground meat.

Illustrations by Keith Witmer

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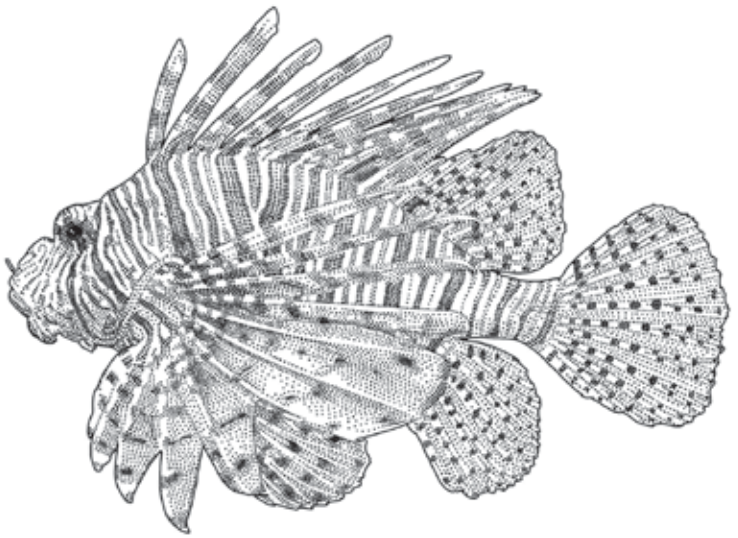
Knot Your Mother's Lemonade

Japanese knotweed grows quickly in clusters and crowds out other herbaceous species. It has been named one of the world's 100 worst invasive species by the International Union for Conservation of Nature and is currently thriving in 41 states. The taste is crunchy, juicy and tart—not unlike a Granny Smith apple. I blend Japanese knotweed shoots in mineral water, ice and a splash of lemon juice, along with fresh stevia and kefir lime leaves.

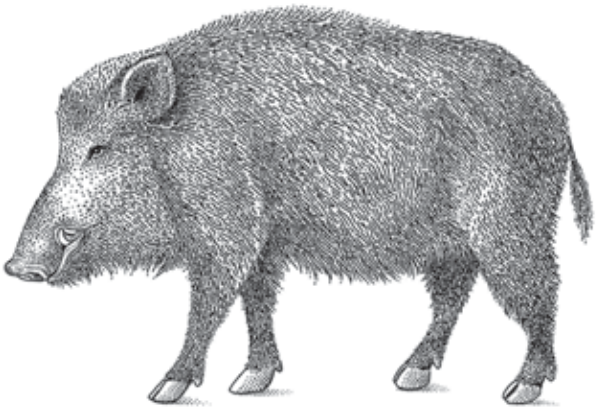
Swarm, Crackle, Pop

The biblical book of Exodus tells of a plague of locusts blackening the ground; after the swarm passed, "Nothing green remained on tree or plant in all the land of Egypt." Locust swarms these days can span 100 square miles and eat 50 million pounds of plants in a day. Swarms migrate great distances: in 1988 one traveled from Africa to the Caribbean in 10 days. These ravenous pests threaten the food security of almost a tenth of humanity—I want to turn the tables on them. As a child, my mother roasted grasshoppers over a fire until the fat in them crackled and popped. My recipe seasons locust and peanuts with a spicy honey teriyaki. I then bake them in the oven until they turn into sweet, crunchy morsels—like Cracker Jack, but with more protein.



Kiribati Sashimi

Lionfish is a voracious, highly poisonous, invasive predator, locustlike in its destructiveness. It was probably introduced to the U.S. by people in the aquarium trade. Protected by highly toxic spines and resembling seaweed, lionfish have few natural enemies. Yet with their dangerous spines removed, their flesh is sweet and delicious. I serve lionfish raw and sliced thin, with a squeeze of lime juice, a sprinkling of seven different kinds of crushed peppers, roasted seaweed flakes and toasted sesame seeds. The dish is topped with sea salt from Kiribati, a Pacific island nation threatened by a sea rising because of climate change.



Oinkimo

Feral hogs were introduced by European explorers in the 1500s; their numbers have exploded in recent years. The pigs eat some native and endangered species and fight for resources with others. But feral hog meat is pharmaceutical-free, unlike most commercial pork, which is raised with antibiotics. I wrap roasted invasive daylily buds in seared, thin-sliced feral hog meat, then drizzle the pig rolls with a ginger, garlic, roasted sesame and sauvignon blanc soy sauce.

Peanut Butter and Jelly

Feral rabbits are some of the most ecologically destructive animals. They procreate uncontrollably, destroy croplands and contribute to soil erosion. Jellyfish populations are expected to explode because of the acidification of the oceans, yet very few cultures appreciate them as a food source. The warty comb jelly, one of the most invasive species on earth, is linked to the collapse of a handful of fisheries. This recipe is my twist on the classic steak-house surf and turf. Invasive cannonball jellyfish, trawled off the state of Georgia, is thin-sliced and mixed with steamed invasive Australian rabbit and cucumber. I season the combination with creamy, roasted peanut butter.

Kudzu Tchaikovsky Sushi

Native to Europe and Asia, the mute swan was introduced to the U.S. as an ornamental species. The swan's majestic looks have earned it protected status in some parts of the U.S., but the swans damage marshes and shallow-water habitats by tearing up vegetation. Kudzu, known as the mile-a-minute plant for how quickly it grows, is in the pea family and was introduced to the U.S. from Asia by gardeners in the 1930s. It creates a canopy and suffocates native forests.

I rub bow-shot swan in a puree of olive oil, freshly grated ginger and Jamaican jerk seasoning, then slow-roast it. The tender dark meat is finely chopped and mixed with roasted shallots and rosemary. I serve it in a steamed kudzu-leaf roll stuffed with a sherry-scented sticky rice and wild morels.

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An overabundance of food choices confronts diners every day. While experts emphasize the benefits of fruits and vegetables, even those foods prompt debate. How important is it, for instance, to go organic?

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NUTRITION

EATING MADE SIMPLE

How do you cope with a mountain of conflicting diet advice?

By Marion Nestle

AS A NUTRITION PROFESSOR, I AM CONSTANTLY ASKED why nutrition advice seems to change so much and why experts so often disagree. Whose information, people ask, can we trust? I'm tempted to say, "Mine, of course," but I understand the problem. Yes, nutrition advice seems endlessly mired in scientific argument, the self-interest of food companies and compromises by government regulators. Nevertheless, basic dietary principles for our weight-conscious society are not in dispute: eat less; move more; eat fruits, vegetables and whole grains; and avoid too much junk food.

"Eat less" means consume fewer calories, which translates into eating smaller portions and steering clear of frequent between-meal snacks. "Move more" refers to the need to balance calorie intake with physical activity. Eating fruits, vegetables and whole grains provides nutrients unavailable from other foods. Avoiding junk food means to shun "foods of minimal nutritional value"—highly processed sweets and snacks laden with salt, sugars and artificial additives. Soft drinks are the prototypical junk food; they contain sweeteners but few or no nutrients.

IN BRIEF

Nutrition advice is confusing. Scientists have difficulty deriving clear guidelines because a study of an individual nutrient fails to produce an understanding of what happens to it when mixed with other nutrients in the body. **The picture** becomes even more clouded because industry groups constantly press their message to both government agencies and consumers about the benefits of eating particular food products. **The simplest message** may be the best: do not overeat; exercise more; consume mostly fruits, vegetables and whole grains; and avoid junk food.

NATASHA V *Gallery Stock*

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If you follow these precepts, other aspects of the diet matter much less. Ironically, this advice has not changed in years. The noted cardiologist Ancel Keys (who died in 2004 at the age of 100) and his wife, Margaret, suggested similar principles for preventing coronary heart disease over 50 years ago [*see box below*].

But I can see why dietary advice seems like a moving target. Nutrition research is so difficult to conduct that it seldom produces unambiguous results. Ambiguity requires interpretation. And interpretation is influenced by the individual's point of view, which can become thoroughly entangled with the science.

CHALLENGES OF NUTRITION SCIENCE

THIS SCIENTIFIC UNCERTAINTY is not overly surprising given that humans eat so many different foods. For any individual, the health effects of diets are modulated by genetics but also by education and income levels, job satisfaction, physical fitness, and the use of cigarettes or alcohol. To simplify this situation, researchers typically examine the effects of single dietary components one by one.

Studies focusing on one nutrient in isolation have worked splendidly to explain symptoms caused by deficiencies of vitamins or minerals. But this approach is less useful for chronic conditions such as coronary heart disease and diabetes that are caused by the interaction of dietary, genetic, behavioral and social factors. If nutrition science seems puzzling, it is because researchers typically examine single nutrients detached from food itself, foods separate from diets, and risk factors apart from other behaviors. This "reductive" kind of research attributes health effects to the consumption of one nutrient or food when it is the overall dietary pattern that really counts most.

For chronic diseases, single nutrients usually alter risk by amounts too small to measure except through large, costly population studies. In many clinical trials of the effects of diet on heart disease, cancer or weight loss, participants were unable to stick with the restrictive dietary protocols. Because humans cannot be caged and fed measured formulas, the diets of experimental and control study groups tend to converge, making differences indistinguishable over the long run—even with fancy statistics.

Organic foods have been shown to leave people who eat them with fewer synthetic pesticides in their bodies than are found in those who consume conventional foods. Proving that organics contain more vitamins or antioxidants is more difficult, but some studies clearly suggest that they do.

IT'S THE CALORIES

FOOD COMPANIES prefer studies of single nutrients because they can use the results to sell products. Add vitamins to candies, and you can market them as health foods. Health claims on the labels of junk foods distract consumers from their caloric content. This practice matters because when it comes to obesity—which dominates nutrition problems even in some of the poorest countries of the world—it is the calories that count. Obesity arises when people consume significantly more calories than they expend in physical activity.

America's obesity rates began to rise sharply in the early 1980s. Sociologists often attribute the "calories in" side of this trend to the demands of an overworked population for convenience foods—pre-

BRIAN MARANAN PINEDA

THE BASICS

Old Advice Still Holds True

In 1959 Ancel and Margaret Keys offered the following precepts—now familiar and still useful—regarding nutrition and activity:

- **Do not get fat; if you are fat, reduce.**
- **Restrict saturated fats: fats in beef, pork, lamb, sausages, margarine and solid shortenings; fats in dairy products.**
- **Prefer vegetable oils to solid fats but keep total fats under 30 percent of your diet calories.**
- **Favor fresh vegetables, fruits and nonfat milk products.**
- **Avoid heavy use of salt and refined sugar.**
- **Good diets do not depend on drugs and fancy preparations.**
- **Get plenty of exercise and outdoor recreation.**

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Omega-3 fatty acids, which are thought by some researchers to protect against heart disease, are found in oily fish such as salmon and trout. The scientific committee tasked with proposing changes to the U.S. Dietary Guidelines for 2015 recommended urging American adults to eat a diet rich in seafood.

pared, packaged products and restaurant meals that usually contain more calories than home-cooked meals.

But other social forces also promoted the calorie imbalance. During the Reagan administration, industry deregulation removed controls on agricultural production and encouraged farmers to grow more food. Calories available per capita in the national food supply (that produced by American farmers, plus imports, less exports) rose from 3,500 a day in 1980 to 4,000 a day three decades later [*see box on next page*].

The early 1980s also marked the advent of the "shareholder-value movement" on Wall Street. Stockholder demands for higher short-term returns on investments forced food companies to expand sales in a marketplace that already contained excessive calories. Food companies responded by seeking new sales and marketing opportunities. They encouraged formerly shunned practices that eventually changed social norms, such as frequent between-meal snacking, eating in book and clothing stores, and serving larger portions.

Then and now, the industry sponsors organizations and journals that focus on nutrition-related subjects and heavily lobbies government for favorable dietary advice. Food lobbies promote positive interpretations of scientific studies, sponsor research that can be used as a basis for health claims, and attack critics, myself among them, as proponents of "junk science." If anything, such activities only add to public confusion.

NUMBERS TO KNOW

Fast Facts

To lose a pound of fat a week, reduce your daily intake by 500 calories.

Carbohydrates and proteins have about 4 calories per gram. Food fats contain more than twice as much: 9 calories per gram. A teaspoon holds about 5 grams.

Alcohol is metabolized in a way that promotes accumulation of fat in the liver, leading to the proverbial beer belly.

An adult expends roughly 100 calories for every mile run or walked briskly. It takes nearly three miles to burn off the calories in a 20-ounce soft drink.

SUPERMARKETS AS "GROUND ZERO"

NO MATTER WHOM I speak to, I hear pleas for help in dealing with supermarkets, which shoppers consider "ground zero" for distinguishing health claims from scientific advice. So I spent a year visiting supermarkets to help people think more clearly about food choices. The result was my book *What to Eat.*

Supermarkets provide a vital public service but are not social-services agencies. Their job is to sell as much food as possible. Every aspect of store design—from shelf position to background music—is based on marketing research [*see box on page 45*]. Because this research shows that the more products customers see, the more they buy, a store's main objective is to expose shoppers to the maximum number of products they will tolerate viewing.

If consumers are confused about which foods to buy, it is surely because the choices require knowledge of issues that are not easily resolved by science and are strongly swayed by social and economic considerations. Such decisions play out every day in every store aisle.

ARE ORGANICS HEALTHIER?

ORGANIC FOODS are the fastest-growing segment of the industry, in part because people are willing to pay more for foods that they believe are healthier and more nutritious. The U.S. Department of Agriculture forbids producers of "Certified Organic" fruits and vegetables from using synthetic pesticides, herbicides, fertilizers, genetically modified seeds, irradiation or fertilizer derived from sewage sludge. It licenses inspectors to ensure that producers follow those rules. Although the USDA is responsible for organics, its principal mandate is to promote conventional agriculture, which explains why the department used to say that it "makes no claims that organically produced food is safer or more nutritious than conventionally produced food." But the USDA has come a long way on organ-

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ics and now proclaims that it "is committed to helping organic agriculture grow and thrive."

Critics of organic foods view them as an explicit critique of industrial agriculture. They question the reliability of organic certification and the productivity, safety and health benefits of organic production methods. Meanwhile the organic food industry longs for research to address such criticisms, but studies are expensive and difficult to conduct.

Nevertheless, research in this area has established that organic farms are nearly as productive as conventional farms, use less energy and leave soils in better condition. People who eat foods grown without synthetic pesticides ought to have fewer such chemicals in their bodies, and they do. Because the organic rules require pretreatment of manure and other steps to reduce the amount of pathogens in soil treatments, organic foods should be just as safe as conventional foods.

Similarly, organic foods ought to be at least as nutritious as conventional foods. And proving organics to be more nutritious could help justify their higher prices. For minerals, this task is not difficult. The mineral content of plants depends on the amounts present in the soil in which they are grown. Organic foods are cultivated in richer soils, so their mineral content is higher.

But differences are harder to demonstrate for vitamins or tissue-protecting antioxidants; higher levels of these nutrients relate more to a food plant's genetic strain or protection from unfavorable conditions after harvesting than to production methods. Some studies do show benefits, though, such as that organic peaches and pears do contain greater quantities of vitamins C and E and that organic berries and corn are richer in antioxidants.

Further research will likely confirm that organic foods contain higher levels of some nutrients, but it is unclear whether these additional nutrients lead to measurable improvements in health. All fruits and vegetables contain useful nutrients, albeit in different combinations and concentrations. Eating a variety of food plants is surely more important to health than small differences in the nutrient content of any one food.

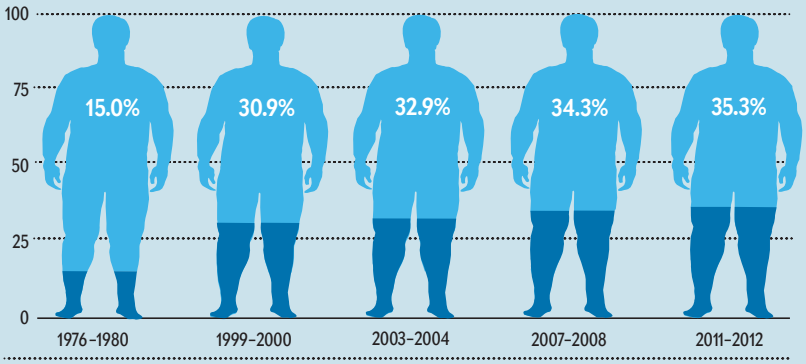
PARALLEL TRENDS

As Food Calories Swell, So Do Waistlines

The substantial rise in U.S. obesity rates during the 1980s and 1990s paralleled increases in the availability of total calories, caloric sweeteners and sugary soft drinks in the food supply, as well as the increasing introduction of "supersize" portions. The adult obesity rates started to stabilize around 2000 as most of these measures began to decline, probably as a result in part of people substituting water, flavored waters and tea drinks for sugary sodas.

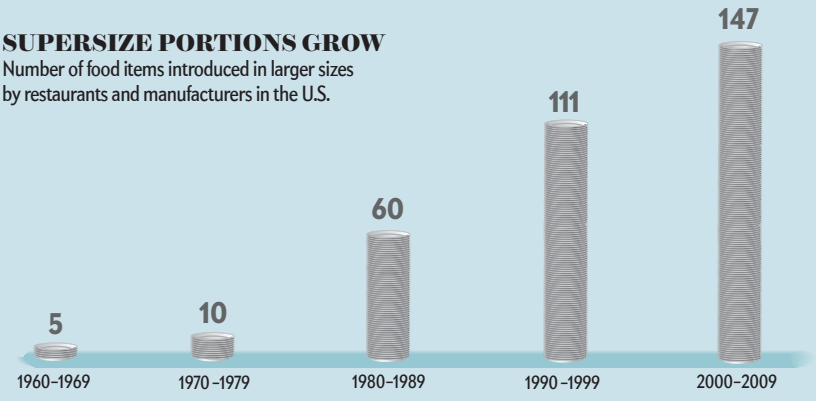
U.S. OBESITY RATES ON THE RISE

Percent of total population (ages 20–74) classified as obese



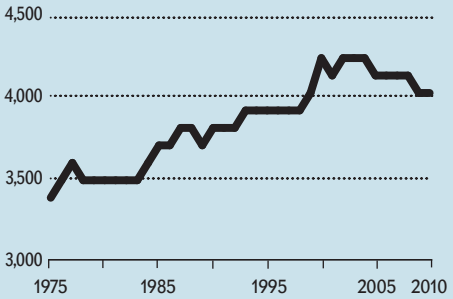
SUPERSIZE PORTIONS GROW

Number of food items introduced in larger sizes by restaurants and manufacturers in the U.S.



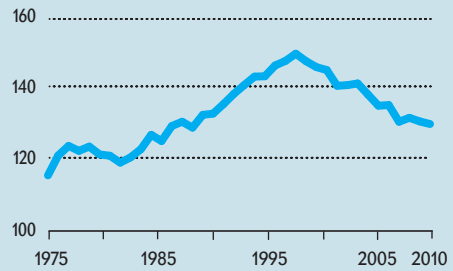
Calories Available

Per person per day in the U.S. food supply



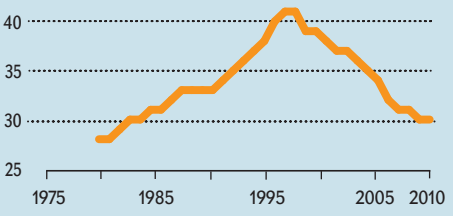
Caloric Sweeteners Available

Pounds per person in the U.S. food supply



Sugary Soft Drinks Available

Gallons per person in the U.S. food supply



JEN CHRISTIANSEN (*graphics*); SOURCES: "PREVALENCE OF OVERWEIGHT, OBESITY, AND EXTREME OBESITY AMONG ADULTS: UNITED STATES, 1960–1962 THROUGH 2011–2012," BY C. D. FRYER, M. D. CARROLL AND C. L. OGDEN, U.S. CENTERS FOR DISEASE CONTROL AND PREVENTION; SEPTEMBER 2014 (*obesity rates*); "REDUCING PORTION SIZES TO PREVENT OBESITY," BY L. R. YOUNG AND M. NESTLE, IN *AMERICAN JOURNAL OF PREVENTIVE MEDICINE*, VOL. 43; 2012 (*portions*); ECONOMIC RESEARCH SERVICE, U.S. DEPARTMENT OF AGRICULTURE (*calories, sweeteners*); BEVERAGE MARKETING CORPORATION (*soft drinks*)

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Whether or not organics are healthier to eat, they are far less likely to damage the environment, and that is reason enough to choose them at the supermarket.

DAIRY AND CALCIUM

SCIENTISTS CANNOT easily resolve questions about the health effects of dairy foods. Milk has many components, and the health of people who consume milk or dairy foods is influenced by everything else they eat and do. But this area of research is especially controversial because it affects an industry that vigorously promotes dairy products as beneficial and opposes suggestions to the contrary.

Dairy foods contribute about 70 percent of the calcium in American diets. This necessary mineral is a principal constituent of bones, which constantly lose and regain calcium during normal metabolism. Diets must contain enough calcium to replace losses, or else bones become prone to fracture. Experts advise consumption of at least one gram of calcium a day to replace everyday losses. Only dairy foods provide this much calcium without supplementation.

But bones are not made of just calcium; they require the full complement of essential nutrients to maintain strength. Bones are stronger in people who are physically active and who do not smoke cigarettes or drink much alcohol. Studies examining the effects of single nutrients in dairy foods show that some nutritional factors—magnesium, potassium, vitamin D and lactose, for example—promote calcium retention in bones. Others, such as protein, phosphorus and sodium, foster calcium excretion. Therefore, bone strength depends more on overall patterns of diet and behavior than simply on calcium intake.

Populations that do not typically consume dairy products appear to exhibit lower rates of bone fracture despite consuming far less calcium than recommended. The incidence of hip fractures in Singapore, for example, is about one fifth of the rate in the U.S., even though Singaporeans consume only about 75 percent as much calcium as Americans do, on average. Why this is so is unclear. Perhaps their diets contain less protein from meat and dairy foods, less sodium from processed foods and less phosphorus from soft drinks, so they retain calcium more effectively. The fact that calcium balance depends on multiple factors could explain why rates of osteoporosis (bone density loss) are highest in countries where people eat the most dairy foods. Further research may clarify such counterintuitive observations.

In the meantime, dairy foods are fine to eat if you like them, but they are not a nutritional requirement. Think of cows: they do not drink milk after weaning, but their bones support bodies weighing 800 pounds or more. Cows feed on grass, and grass contains calcium in small amounts—but those amounts add up. If you eat plenty of fruits, vegetables and whole grains, you can have healthy bones without having to consume dairy foods.

Some obese children in the U.S. consume 1,000 calories a day (equal to about 59 sugar cubes) in sweetened beverages alone. That is equivalent to more than three 20-ounce bottles of soft drinks.

BRIAN MARANAN PINEDA

A MEATY DEBATE

CRITICS CLAIM THAT eating meat elevates blood cholesterol as well as the risks for heart disease, cancer and other conditions. Meat proponents cite the lack of compelling science to justify such allegations; they emphasize the nutritional benefits of meat protein, vitamins and

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minerals. Indeed, studies in low-income countries demonstrate that when growing children eat even small amounts of meat, their health improves.

But because bacteria in a cow's rumen attach hydrogen atoms to unsaturated fatty acids, beef fat is highly saturated—the kind of fat that increases the risk of coronary heart disease. All fats and oils contain some saturated fatty acids, but animal fats, especially those from beef, have more saturated fatty acids than vegetable fats. Nutritionists recommend eating no more than a heaping tablespoon (20 grams) of saturated fatty acids a day. Beef eaters easily meet or exceed this limit. The smallest McDonald's cheeseburger contains six grams of saturated fatty acids, but a Hardee's Monster Thickburger has 45 grams.

Why red and processed meats might boost cancer risks, however, is a matter of speculation. Scientists began to link such meats to cancer in the 1970s, but even after decades of subsequent research they remain unsure if the relevant factor might be fat, saturated fat, protein, carcinogens or something else related to eating these foods. By the late 1990s experts could conclude only that eating beef and processed meat convincingly increases the risk of colon and rectal cancers and possibly enhances the odds of acquiring lung, prostate and perhaps other cancers. Faced with this uncertainty, the American Cancer Society suggests selecting leaner cuts, smaller portions, and alternatives such as chicken, fish or beans—steps consistent with today's basic advice about what to eat.

What to eat: fruits, vegetables and whole grains constitute the main components of a healthy diet.

BRYAN MARANAN PINEDA

FISH AND HEART DISEASE

FATTY FISH are the most important sources of long-chain omega-3 fatty acids. In the early 1970s Danish investigators observed surprisingly low frequencies of heart disease among indigenous populations in Greenland that typically ate fatty fish, seals and whales. The researchers attributed the protective effect to the foods' content of omega-3 fatty acids. Some subsequent studies—but by no means all—confirm this idea.

Because large, fatty fish are likely to have accumulated methylmercury and other toxins through predation, however, eating them raises questions about the balance between benefits and risks. Understandably, the fish industry is eager to prove that the health benefits of omega-3s outweigh any risks from eating fish.

Even independent studies on omega-3 fats can be interpreted differently. In 2004 the National Oceanic and Atmospheric Administration—for fish, the agency equivalent to the USDA—asked the Institute of Medicine (IOM) to review studies of the benefits and risks of consuming seafood. The ensuing review of the research on heart disease risk illustrates the challenge such work poses for interpretation.

The IOM's 2006 report concluded that eating seafood reduces the risk of heart disease but judged the studies too inconsistent to decide if omega-3 fats were responsible. In contrast, investigators from the Harvard School of Public Health published a much more positive report in the *Journal of the American Medical Association* that same year. Even modest consumption of fish omega-3s, they stated, would cut coronary deaths by 36 percent and total mortality by 17 percent, meaning that not eating fish would constitute a health risk.

Differences in interpretation explain how distinguished scientists could arrive at such different conclusions after considering the same studies. The two groups, for example, had conflicting views of work that had recently appeared in the *British Medical Journal*. That study found no overall effect of omega-3s on heart disease risk or mor-

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tality, although a subset of the original studies displayed a 14 percent reduction in total mortality that did not reach statistical significance. The IOM team interpreted the "nonsignificant" result as evidence for the need for caution, whereas the Harvard group saw the data as consistent with studies reporting the benefits of omega-3s.

When studies present inconsistent results, both interpretations are plausible. I favor caution in such situations, but not everyone agrees.

Because findings are inconsistent, so is dietary advice about eating fish. The American Heart Association recommends that adults eat fatty fish at least twice a week, but the 2010 U.S. Dietary Guidelines made no specific recommendation about fish and heart disease except that pregnant and breastfeeding women should consume eight to 12 ounces of seafood per week. Of this, only six ounces should come from tuna and none from fish even higher in methylmercury. Whether or not fish uniquely protects against heart disease, seafood is a delicious source of many nutrients, and two small servings per week of the less predatory fish are unlikely to cause harm.

SODAS AND OBESITY

SUGARS AND CORN sweeteners account for a large fraction of the calories in many supermarket foods, and virtually all the calories in drinks—soft, sports and juice—come from added sugars.

In a trend that correlates closely with rising rates of obesity, daily per capita consumption of sweetened beverages grew dramatically during the 1980s and 1990s. Since 1998, U.S. production of sugary sodas has declined, and the obesity rate has stabilized.

Common sense suggests that soda drinking might have something to do with weight gain, but beverage makers argue that studies cannot prove that sugary drinks alone—independent of calories or other foods in the diet—boost the risk of obesity. The evidence, they say correctly, is circumstantial. But pediatricians frequently treat obese children who consume more than 1,000 calories a day from sweetened drinks, and numerous studies indicate that children who habitually consume sugary beverages take in more calories and weigh more than those who do not.

SAVVY SHOPPING

Designer Supermarkets

Marketing experts design nearly every feature of food stores—from product placement to mood music—to maximize sales.

When customers enter a grocery store, the first thing they see is typically something colorful, aromatic and enticing—fresh produce, for example.

The long center aisles and aisle-end displays are jam-packed with products, forcing shoppers to pass by many items that they might purchase on impulse.

Food companies pay supermarkets to get their products—salty chips and other junk foods—positioned prominently in huge displays.

Checkout lines are plastered with candy and other junk food items—the last temptation.

Nevertheless, the effects of sweetened drinks on obesity continue to be subject to interpretation. In 2006, for example, a systematic review funded by independent sources found sweetened drinks to promote obesity in both children and adults. But a review that same year sponsored in part by a beverage trade association concluded that soft drinks have no special role in obesity. The industry-funded researchers criticized existing studies as being short-term and inconclusive and pointed to studies finding that people can lose weight even when they substitute sweetened drinks for their usual meals.

These differences imply the need to scrutinize food industry sponsorship of research itself. Although many researchers are offended by suggestions that funding support might affect the way they design or interpret studies, systematic analyses say otherwise. In 2007 investigators classified studies of the effects of sweetened and other beverages on health according to who had sponsored them. Industry-supported studies were more likely to yield results favorable to the sponsor than those funded by independent sources. Subsequent studies confirmed this effect of funding source on study outcome. Even though scientists may not be able to prove that sweetened drinks cause obesity, it makes sense for anyone interested in losing weight to consume less of them.

The examples I have discussed illustrate why nutrition science seems so controversial. Without improved methods to ensure compliance with dietary regimens, research debates are likely to rage unabated. Opposing points of view and the focus of studies and food advertising on single nutrients rather than on dietary patterns continue to fuel these disputes. While we wait for investigators to find better ways to study nutrition and health, my approach—eat less, move more, eat a largely plant-based diet, and avoid eating too much junk food—makes sense and leaves you plenty of opportunity to enjoy your dinner. SA

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MORE TO EXPLORE

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NEUROSCIENCE

THE FOOD ADDICTION

New brain research is revealing why fats and sugars may be driving more and more people toward obesity

By Paul J. Kenny

IN BRIEF

Recent science shows that overeating is not a behavioral disorder, such as a lack of self-control. Nor is it always the result of a hormonal imbalance. A primary culprit is sweet, high-fat food itself.

Sugary, fatty foods can supercharge the brain's reward system, overpowering the brain's ability to curb an individual's appetite. In such cases, the more someone eats, the more he or she wants.

Is that addiction? The question matters only if it leads to effective treatments. A drug that reduces nicotine cravings in smokers can also reduce the desire for food, but it has dangerous side effects.

Researchers need to know whether the brain's overeating networks are the same as its drug addiction pathways and, if so, whether addiction treatments can reduce the harm caused by obesity.

Photoillustration by James Worrell

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WOULD A RAT RISK DYING JUST TO SATISFY ITS DESIRE FOR CHOCOLATE?

A few years ago I found out. In my laboratory, we gave rats unlimited access to standard chow as well as to a mini cafeteria full of appetizing, high-calorie foods: sausage, cheesecake, chocolate. The rats decreased their intake of the healthy but bland items and switched to eating the cafeteria food almost exclusively. They gained weight. They became obese.

We then warned the rats as they were eating—by flashing a light—that they would receive a nasty foot shock. Rats eating the bland chow would quickly stop and scramble away, but time and again the obese rats continued to devour the rich food, ignoring the warning that they had been trained to fear. Their hedonic desire overruled their basic sense of self-preservation.

Our finding mirrored a previous trial conducted by Barry Everitt of the University of Cambridge—only his rats were hooked on cocaine.

So are the fat rats addicted to food? An inability to suppress a behavior, despite the negative consequences, is common in addiction. Scientists are finding similar compulsiveness in certain people. Almost all obese individuals say they want to consume less, yet they continue to overeat even though they know that doing so can have shockingly negative health or social consequences. Studies show that overeating juices up the reward systems in our brain—so much so in some people that it overpowers the brain's ability to tell them to stop eating when they have had enough. As with alcoholics and drug addicts, the more they eat, the more they want. Whether or not overeating is technically an addiction, if it stimulates the same brain circuits as drug use, in the same way, then medications that dial down the reward system could help obese people to eat less.

SUSPICIOUS HORMONES

UNTIL THE EARLY 1990S, society viewed obesity solely as a behavioral disorder: overweight individuals lacked willpower and self-control. Since then, the view has changed dramatically, in the scientific community at least.

The first change in opinion arose from pioneering work by the late Douglas Coleman of Jackson Laboratory in Bar Harbor, Me., and by Jeffrey Friedman of the Rockefeller University. Experiments with two strains of mice, both genetically prone to obesity and diabetes, determined what drove the mice to overeat. The researchers discovered that one strain had a genetic defect in fat cells that secrete a hormone called leptin. Mice, like humans, normally secrete leptin after a meal to suppress appetite and prevent overeating. The obese mice had a leptin deficiency—and an insatiable appetite. Later the researchers found that obesity in the second strain of mice was caused by a genetic defect in their ability to respond to leptin and regulate its actions. The findings seemed to make it clear that hormones regulate appetite and therefore body weight. A hormonal imbalance could lead to overeating; indeed, obesity runs rampant in certain human families that have a genetic deficiency in leptin.

Two observations suggest that viewing obesity as a hormone disorder is too simplistic, however. First, only a small number of obese people in the U.S. and elsewhere have a genetic deficiency in appetite-related hormones. Second, if obesity is driven purely by hormonal imbalances, then blood tests of obese people ought to show either a lower level of hormones that suppress appetite or a higher level of hormones that increase appetite. Yet the reverse is true. Obese individuals generally have a paradoxically high level of appetite-suppressing hormones, including leptin and insulin.

This is where the concept of food addiction comes into play. Appetite-controlling hormones affect certain pathways of neurons—we call them feeding circuits—in the hypothalamus. These hormones also affect systems in the brain that control feelings of reward, which makes sense. If you have not eaten for many hours, you will spend a lot of time, effort and money to obtain food—and it will taste very good! As the old adage says, "Hunger is the best sauce."

During periods of hunger, hormones heighten the reactivity of food-related reward circuits in the brain, particularly in the striatum [*see box on opposite page*]. The striatum contains high concentrations of endorphins—chemicals that enhance feelings of pleasure and reward.

As you eat, your stomach and gut release appetite-suppressing hormones that decrease pleasure signals that are triggered by the striatum and other components of the reward system. This process makes food seem less attractive, and you may switch your activity away from eating and toward other pursuits. The suite of appetite-regulating hormones controls feeding, in part by modulating the pleasurable experience of consuming a meal.

Yet some modern, appetizing foods—especially those that are fatty, sugary and visually appealing—affect reward systems strongly enough to override the appetite-

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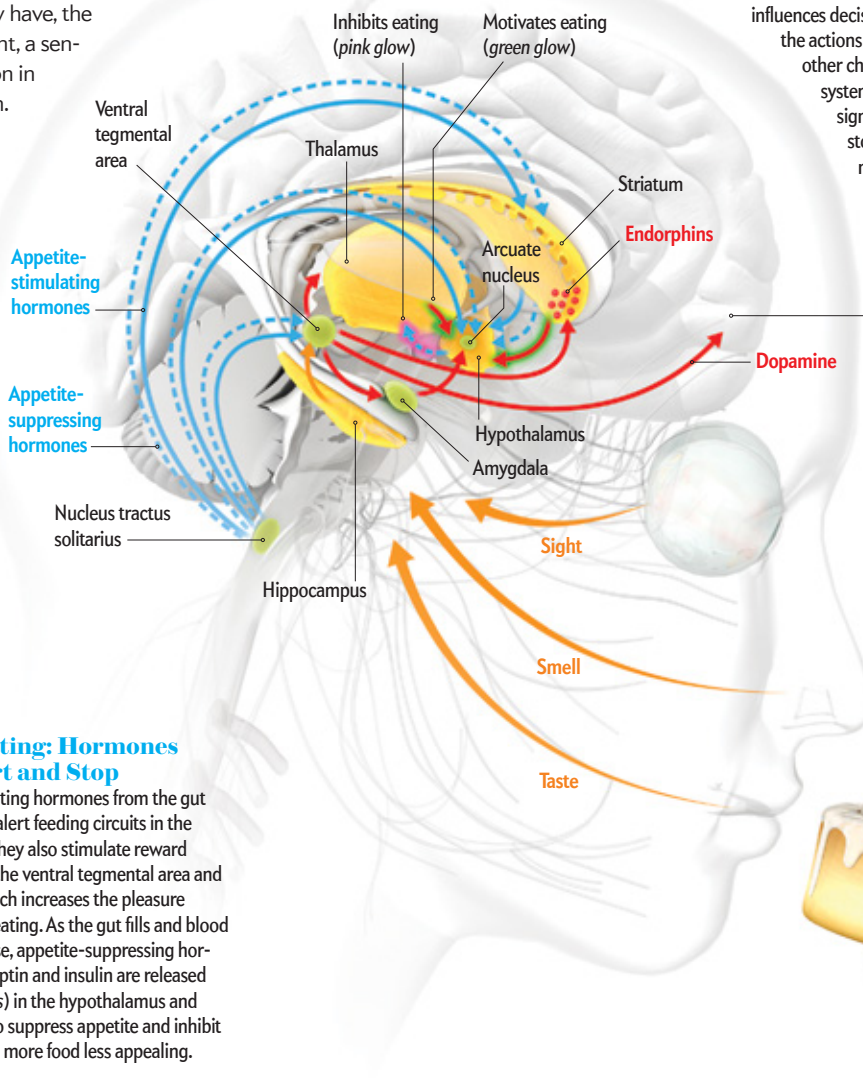
Hooked on Food

Our brains maintain healthy body weight by signaling when to eat and when to stop. Hormones regulate feeding circuits that control appetite and satiety (*blue*). But fatty, sugary foods can motivate some people to overeat (*red*). The more they have, the more they want, a sensation common in drug addiction.



Overeating: Brain Chemicals Hijack the Controls

Foods that are dense in fat and sugar prompt the striatum to make endorphins, "feel good" chemicals that can trigger binge eating. The foods also spark dopamine release (*red lines*) by the striatum, which motivates feeding behavior, and into the prefrontal cortex, which influences decision making. In some people, the actions of endorphins, dopamine and other chemicals that regulate reward systems can overpower hormonal signals and conscious attempts to stop eating when full. A strong motivation to eat high-calorie foods prevails despite an individual's knowledge about health consequences.

Treatment Prospects

Addictive drugs lead to dopamine release and feedback loops in the brain that can spur people to seek more and more—just as overeating high-calorie foods can do. Medications that could break this cycle could possibly ease not only drug addiction but obesity.

Normal Eating: Hormones Signal Start and Stop

Appetite-stimulating hormones from the gut (*solid blue lines*) alert feeding circuits in the hypothalamus. They also stimulate reward centers, such as the ventral tegmental area and the striatum, which increases the pleasure associated with eating. As the gut fills and blood nutrient levels rise, appetite-suppressing hormones such as leptin and insulin are released (*dashed blue lines*) in the hypothalamus and reward centers to suppress appetite and inhibit pleasure, making more food less appealing.

suppressing hormones, thus prompting us to eat when we would not otherwise feel hungry. These foods activate our reward circuits more powerfully than leptin's ability to shut them down. All of us have experienced this effect: you have just finished a big dinner and could not possibly eat another bite. Yet when the chocolate cake appears, you can miraculously "find room" for one last morsel—one that happens to be the most calorie-laden of the day.

Therein lies the rub. We have evolved an efficient brain system to help maintain a healthy and consistent body weight by signaling when it is time to eat and when it is time to stop. But highly appetizing foods can often veto these signals and drive weight gain.

Our body responds to the override by elevating the blood levels of the appetite-suppressing hormones higher and higher as body weight increases, yet the hormones become progressively less effective as the body build ups a tolerance to their actions. Moreover, brain-imaging studies by researchers at Brookhaven National Laboratory and the Oregon Research Institute show that the brain's reward systems in overweight individuals may actually respond less strongly to food—even to junk food—than they do in people of healthy weight. These muffled reward circuits depress mood. How does an individual overcome this funk? By eating more delectable food to gain a temporary boost, thereby perpetuating the cycle. The

Illustration by Bryan Christie

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obese, in other words, may have to overeat just to experience the same degree of pleasure that lean people enjoy from less food.

Obesity, it seems, is not caused by a lack of willpower. And it is not always caused by an imbalance in hormones. In some cases at least, obesity may be caused by hedonic overeating that hijacks the brain's reward networks. Like addictive drugs, overeating creates a feedback loop in the brain: the more you consume, the more you crave, and the harder it is to satisfy that craving.

But does that make hedonic eating an addiction?

TOLERANCE AND RELAPSE

DRUGS OF ABUSE, such as morphine, stimulate the brain's reward systems in the same way that food does. Yet the similarities do not end there. When morphine is injected into the striatum of rats, it triggers bingelike overeating, even in rats that have been fed to satiety. This response shows that morphine and other opiates mimic the effects of neurotransmitters (brain chemicals) such as endorphins that are naturally produced in the brain to stimulate feeding behaviors.

We might expect, then, that drugs that block the action of endorphins could reduce hedonic overeating. Recent studies have shown that endorphin blockers do lessen the activation of reward circuits in humans and rodents that are presented with appetizing food, and the subjects eat less. The blockers can also reduce heroin, alcohol and cocaine use in human drug addicts, supporting the idea that common mechanisms regulate hedonic overeating and addictive drug use. Strikingly, rats that are allowed to binge on food every day and then are treated with endorphin blockers display behaviors that closely resemble withdrawal, a symptom of drug addiction. That result suggests that hedonic overeating can induce a brain state akin to drug dependence.

These discoveries add credence to the idea that overeating in some circumstances may share core features of drug addiction. So do similarities that we see with another basic neurotransmitter: dopamine. All known addictive drugs lead to the release of dopamine into the striatum. Dopamine is central to motivation; it spurs people to seek drugs. Most experts maintain that this action drives the development of addiction, although the precise mechanisms are hotly debated. It turns out that appetizing food also stimulates the release of dopamine into the striatum, motivating people to focus on obtaining and consuming food.

Paradoxically, obese rats and mice produce very low levels of dopamine, probably because their brain reward systems adapt to constant overstimulation by appetizing food. Lower dopamine levels in obese individuals may drive overeating just to obtain the same level of pleasure from food as that derived by lean individuals. In exciting work from a group led by Ivan de Araujo of Yale University, mice fed a high-fat diet were found to have lower circulating levels of a fat called oleoylethanolamine, which is produced by the gut. Remarkably, when this compound was injected into overweight mice, levels of dopamine returned to normal, and the mice ate more low-fat food and less high-fat food.

OBESITY IS DRIVEN BY AN OVERPOWERING MOTIVATION TO SATISFY THE BRAIN'S REWARD CENTERS; HORMONE ISSUES MAY BE A CONSEQUENCE, NOT A CAUSE.

Imaging studies have illuminated other connections between eating and addiction. The striatum of obese individuals shows low levels of a receptor that responds to dopamine, the dopamine D2 receptor (D2R). Those suffering from alcoholism or from opiate, cocaine or methamphetamine addiction similarly tend to have low levels of D2R. And we now know that people who are born with a D2R deficiency are at greater genetic risk of developing both obesity and drug addiction. The condition results in lower levels of activity in the brain's reward systems, suggesting that overeating is just a coping behavior to obtain normal pleasure from eating. These people also tend to have trouble learning to avoid actions that have negative consequences; brain systems involved in suppressing risky yet rewarding behaviors, such as consuming high-calorie food or using drugs, may not work as effectively.

Our lab study of rats backs up this idea. The obese rats that ate the cafeteria food, ignoring warnings about being shocked, had low levels of D2R in the striatum. These experiments and others demonstrate that drug use in addicted rats and hedonic eating in overweight rats persist even when the animals face negative consequences. Many obese individuals struggle so badly with their poor food choices that they voluntarily undergo risky procedures, such as gastric bypass surgery, to help them control their eating. Yet very often they relapse to overeating and gain weight.

This cycle of engaging in a bad habit that gives short-term pleasure and then attempting to abstain from it and eventually relapsing sounds disturbingly like drug addiction. Given the latest research, it seems that obesity is caused by an overpowering motivation to satisfy the reward centers—the pleasure centers—of the brain. The hormonal and metabolic disturbances in obese individuals may be a consequence of weight gain rather than a cause.

NEW TREATMENTS POSSIBLE

THE SIMILARITIES between obesity and addiction have led some experts to say that the two conditions should be treated in the same manner—in particular, that obesity be included in the most recent update to the *Diagnostic and Statistical Manual of Mental Disorders*—the bible of psychiatry that provides guidelines for diagnosing mental illnesses, known as the *DSM-5*. This proposal sparked lively debate among neuroscientists and psychiatrists, but arbiters for the *DSM-5* ultimately dropped the idea, largely to avoid obese people being labeled as mentally ill.

Caution may have been warranted because despite the parallels, obesity and addiction differ in important ways. For example, if food is addictive, then surely it

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must contain some unique component that drives the addiction—the nicotine of junk food, if you will. Work by Nicole Avena, now at the Icahn School of Medicine at Mount Sinai, the late Bartley Hoebel of Princeton University and others lends some credence to the idea that particular fats or sugars may be responsible. A small study by David Ludwig of Boston Children's Hospital suggests that highly processed, quickly digested carbohydrates could trigger cravings. But research overall indicates that no one ingredient stokes addictionlike behaviors. Rather the combination of fats and sugars, together with calorie content, seems to maximize food's "hedonic impact."

Other experts, including Hisham Ziauddeen, I. Sadaf Farooqi and Paul C. Fletcher of the University of Cambridge, have argued that tolerance and withdrawal do not occur in obese people in the same way that they do in drug addicts—obesity and drug addiction, they say, are fundamentally different.

This view is debatable. If obese individuals must eat more and more to overcome reduced activation of reward networks in the brain, that sounds a lot like tolerance. And weight loss can trigger negative mood and depression, much like that experienced by former addicts who try to practice abstinence, suggesting that withdrawal may be in effect.

Another objection experts have raised is that it is preposterous to apply the concept of addiction to eating because we are all, in a sense, addicted to food. If we were not, we would not survive.

The difference in obesity, I would suggest, is that modern high-calorie foods can overwhelm our biological feedback networks in a way that other foods do not. During millions of years of evolution, the major concern of humans was not suppressing appetite but hunting, collecting or growing enough food to persist in lean times. Perhaps our feeding circuits are better at motivating food intake when we are hungry than they are at suppressing food intake when we are full. It is easy to imagine that the brain would regard overeating of high-calorie food as tremendously beneficial if it is uncertain when food will again be available. But this behavior is no longer adaptive and can be counterproductive in a world where food is bountiful.

Scientists have made fair points in arguing against an addiction model of obesity. I, too, fear that the term "addiction" comes loaded with unhelpful preconceptions. Still, compulsive eating and compulsive drug use seem to share obvious features, most notably an inability to control consumption. It is up to scientists to determine whether these similarities are superficial or stem from common alterations in the brain. More important, we must determine whether the addiction model is useful. Unless it helps us design new treatment approaches, the debate is simply an academic exercise.

For an addiction model to have value, it should make accurate predictions about treatment options, including new medications. One example comes from Arena Pharmaceuticals, which obtained approval from the U.S. Food and Drug Administration in 2012 to market a drug called Belviq (lorcaserin) for weight loss in obese or overweight adults. The drug stimulates a brain protein, the serotonin 2C receptor, that is involved in satiety.

Another drug is rimonabant, which had been approved in Europe to help curb appetite in obese individuals. The drug exploits the well-known property of cannabis to increase desire for food—the so-called munchies. Cannabis activates a brain protein called the cannabinoid receptor 1, so researchers reasoned that inhibiting that receptor would decrease desire for food. Rimonabant does exactly that. A notable side effect is its ability to decrease tobacco users' desire to smoke. In rats, the drug also decreases the desire to use alcohol, opiates and stimulants such as cocaine.

As with all new drugs, however, caution is required. Both Belviq and rimonabant have triggered depression in some individuals. Rimonabant was linked to an increased risk of suicidal thoughts. This finding led European authorities to remove rimonabant from the market and prompted U.S. officials to not approve it. Why depression emerged is still unclear. Although an addiction model of obesity may yield new treatments, they must be thoroughly scrutinized.

Before scientists can declare that overeating is or is not an addiction, they will have to identify precisely which networks and cellular adaptations in the brain drive compulsive drug use and then determine if the same mechanisms also motivate compulsive food intake. It is likely that addiction networks for cocaine and for food operate in different parts of the brain yet use similar mechanisms. For example, recent work on compulsive sugar eating has implicated projections that connect the lateral hypothalamus to the midbrain neurons that synthesize dopamine. But it is not clear yet whether this circuit plays a similar role in drug seeking.

Scientists are also stuying whether common genetic variations, such as those that affect D2R, contribute to drug addiction and obesity. Identifying such genes may reveal new targets for medications to treat both disorders.

Even if researchers eventually prove that obesity sometimes arises from an addiction to food, and we find that antiaddiction medications can help people lose weight, obese individuals will continue to struggle with one factor that seems now to be endemic in America: they will probably be surrounded by overweight family members, friends and co-workers who are still overeating, putting them in the same difficult environment they were in before. As we know from recovering drug addicts and alcoholics, environmental cues are a major cause of craving and relapse. Western society, saturated in fat and temptation, will make it hard for any obese person to quit. SA

Paul J. Kenny is Ward-Coleman Professor and chair of the department of pharmacology and systems therapeutics at the Icahn School of Medicine at Mount Sinai. He studies drug addiction, obesity and schizophrenia.

MORE TO EXPLORE

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HEALTH

HOW TO FIX THE OBESITY CRISIS

Although science has revealed a lot about metabolic processes that influence our weight, the key to success may lie elsewhere

By David H. Freedman

OBESITY IS A NATIONAL HEALTH CRISIS—THAT MUCH WE KNOW. IF CURRENT TRENDS continue, it will soon surpass smoking in the U.S. as the biggest single factor in early death, reduced quality of life and increased health care costs.

A third of adults in the U.S. are obese, according to the Centers for Disease Control and Prevention, and another third are overweight, with Americans getting fatter every year. Obesity is responsible for more than 160,000 "excess" deaths a year, according to a study in the *Journal of the American Medical Association*. The average obese person costs society more than $7,000 a year in lost productivity and extra medical treatment, say researchers at George Washington University. Lifetime-added medical costs alone for a person 70 pounds or more overweight amount to as much as $30,000, depending on race and gender.

All this lends urgency to the question: Why are extra pounds so difficult to shed and keep off? It does not seem as though it should be so hard. The basic formula for weight loss is simple and widely known: consume fewer calories than you expend. And yet if it really were easy, obesity would not be the nation's number-one lifestyle-related health concern. For a species that evolved to consume energy-dense foods in an environment where famine was a constant threat, losing weight and staying trimmer in a modern world of plenty fueled by marketing messages and cheap empty calories is, in fact, terrifically difficult. Almost everybody who tries to diet seems to fail in the long run—a review in 2007 by the American Psychological Association of 31 diet studies found that as many as two thirds of dieters end up two years later weighing *more* than they did before their diet.

Science has trained its big guns on the problem. The National Institutes of Health has been spending more than $800 million a year on studies to understand the metabolic, genetic and neurological foundations of obesity. In its strategic plan for funding obesity research, published in 2011, the NIH placed at the top of the list of research opportunities the investigation of basic biological processes related to obesity, including "specific roles of organs, tissues, and molecules in the development of obesity" and "genes, epigenetics, and critical periods in human development."

This research has provided important insights into the ways proteins interact in our body to extract and distribute energy from food and produce and store fat; how our brain tells us we are hungry; why some of us seem to have been born more likely to be obese than others; and whether exposure to certain foods and toxic substances might modify and mitigate some of these factors. The work has also given pharmaceutical companies numerous potential targets for drug development. What the research has not done, unfortunately, is make a dent in solving the national epidemic.

Maybe someday biology will provide us with a pill that readjusts our metabolism so we burn more calories or resets

Illustration by Bryan Christie

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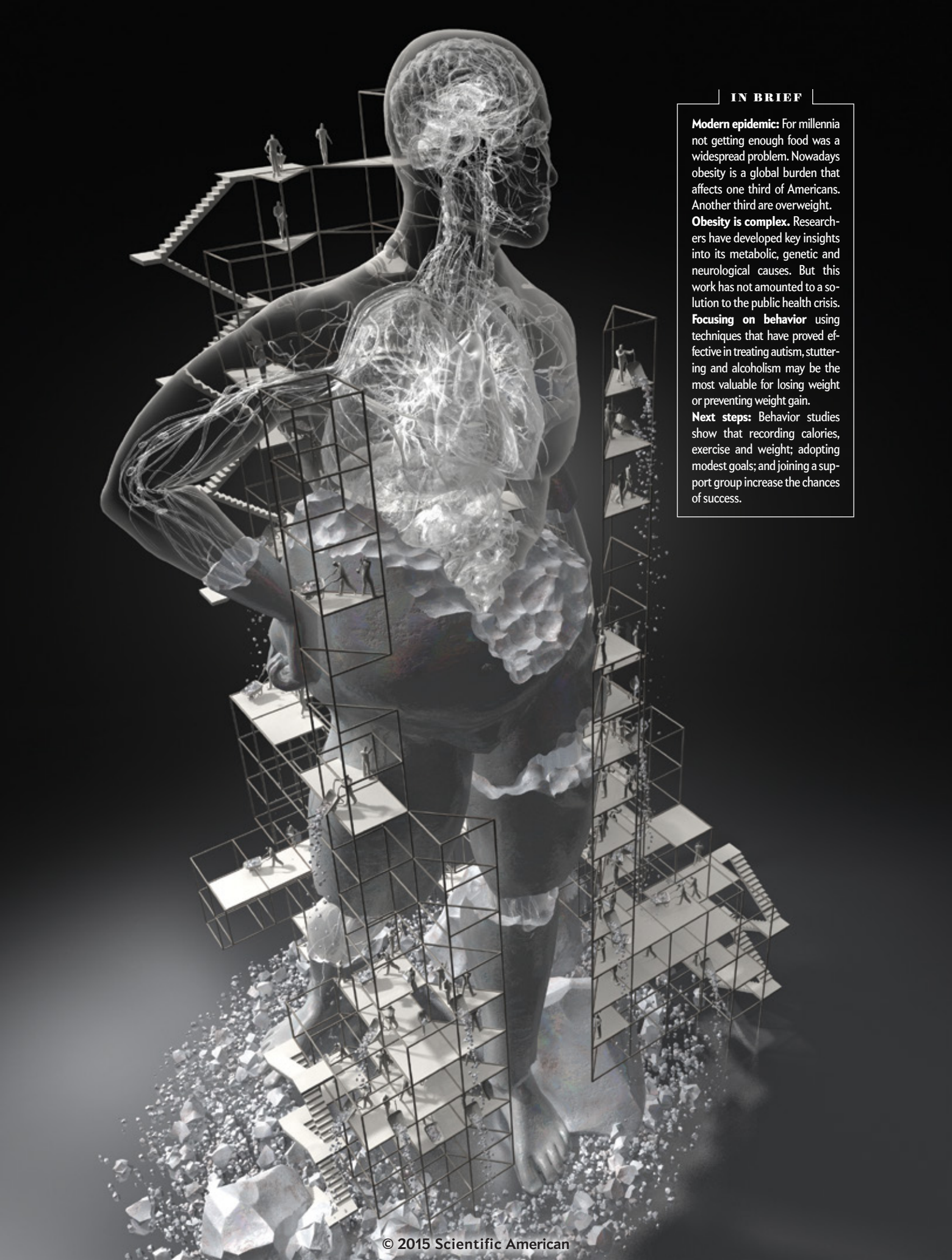

IN BRIEF

Modern epidemic: For millennia not getting enough food was a widespread problem. Nowadays obesity is a global burden that affects one third of Americans. Another third are overweight.

Obesity is complex. Researchers have developed key insights into its metabolic, genetic and neurological causes. But this work has not amounted to a solution to the public health crisis.

Focusing on behavior using techniques that have proved effective in treating autism, stuttering and alcoholism may be the most valuable for losing weight or preventing weight gain.

Next steps: Behavior studies show that recording calories, exercise and weight; adopting modest goals; and joining a support group increase the chances of success.

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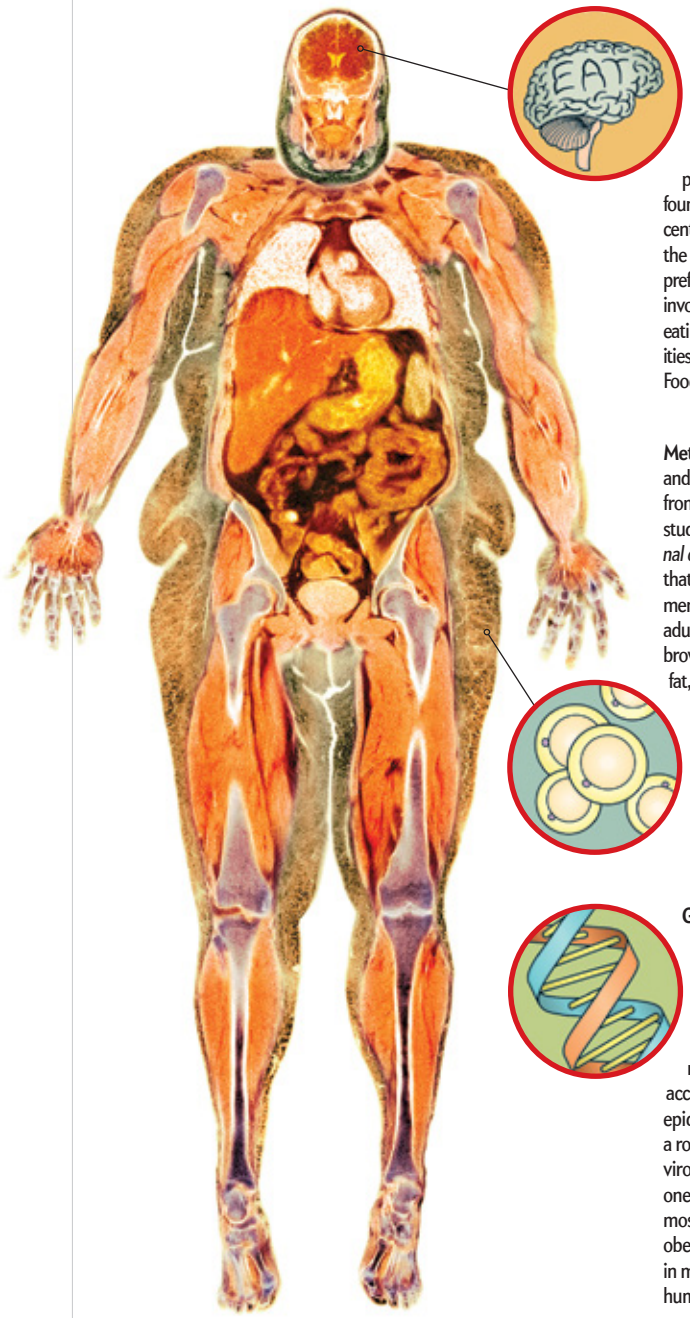
ADVANCES IN THE LAB

The Biology of Obesity

The National Institutes of Health has spent more than $800 million a year on studies to understand the neurological, metabolic and genetic foundations of obesity. In the process, scientists have uncovered complex biochemical pathways and feedback loops that connect the brain and digestive system; a new appreciation for the regulatory functions of fat tissues; subtle hereditary changes that make some groups more prone to obesity than others; and the strong possibility that exposure to certain foods and toxic substances might modify and mitigate some of these factors. Given that it will likely take decades to understand the various causes of obesity, more surprises are no doubt in store.



Brain: Scientists have long known that the hypothalamus and brain stem help to regulate feelings of hunger and fullness. Over the past decade researchers have found that the pleasure-reward centers of the limbic system and the evaluating functions of the prefrontal cortex are also heavily involved. Indeed, chronic overeating bears biochemical similarities to drug addiction [see "The Food Addiction," on page 46].

Metabolism: The ability to burn and store energy varies greatly from cell to cell. In 2009 three studies in the *New England Journal of Medicine* demonstrated that at least some women and men continue to benefit well into adulthood from small stores of brown fat, which, unlike white fat, is associated with being lean. Brown fat helps to generate heat and is apparently more closely related to muscle than to white fat, whose primary purpose is to store excess energy.

Genes: Researchers have confirmed variations in 20-odd genes that predispose people to gaining weight easily. But further investigation shows that the effects are modest at best and cannot account for the current obesity epidemic. Genes may still play a role, however, through the environment's influence on which ones get turned on or off. So far most such genetic switches for obesity have been identified in mice, although a few likely human candidates are known.

our built-in cravings so we prefer broccoli to burgers. But until then, the best approach may simply be to build on reliable behavioral-psychology methods developed over 50 years and proved to work in hundreds of studies. These tried-and-true techniques, which are being refined with new research that should make them more effective with a wider range of individuals, are gaining attention. As the NIH puts it in its proposed strategic plan for obesity research: "Research findings are yielding new and important insights about social and behavioral factors that influence diet, physical activity, and sedentary behavior."

HOW WE GOT HERE

THE DESPERATION OF the obese and overweight is reflected in the steady stream of advice pouring daily from sources as disparate as peer-reviewed scientific journals, best-selling books, newspapers and blogs. Our appetite for any diet twist or gimmick that will take the pounds off quickly and for good seems to be as insatiable as our appetite for the rich food that puts the pounds on. We, the public, love to believe in neat fixes, and the media oblige by playing up new scientific findings in headline after headline as if they are solutions.

It does not help that the scientific findings on which these headlines are based sometimes appear to conflict. For example, a 2010 study in the *American Journal of Clinical Nutrition* linked weight loss to increased dairy intake, although a 2008 meta-analysis in *Nutrition Reviews* found no such link. A 2010 paper in the *Journal of Occupational and Environmental Medicine* postulated a connection between job stress and obesity, but another report that year in the journal *Obesity* concluded the two are uncorrelated. Part of the problem is that obesity researchers are in some ways akin to the metaphorical blind men groping at different parts of the elephant: their individual study findings address only narrow pieces of a complex puzzle.

When the research is taken together, it is clear that the obesity fix cannot be boiled down to eating certains kinds of food or taking other simple actions. Many factors contribute to the problem. Some are environmental—the eating habits of your friends, what food is most available in your home and your local stores, how much opportunity you have to move around at work. Others are biological, such as genetic predispositions for stor-

GUSTOIMAGES *Science Source (MRI)*

Illustrations by Peter and Maria Hoey

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ing fat, having higher satiety thresholds or having more sensitive taste buds. Economics and marketing play roles, too. Junk food is much cheaper than fresh produce. And food companies are masters at manipulating our social nature and our evolutionary "programming" to steer us toward unhealthy but profitable fare. That is why the narrow "eat this" kinds of solutions, like all simple solutions, fail.

When we go on diets and exercise regimens, we rely on willpower to overcome all these pushes to overeat relative to our activity level. And we count on the reward of getting trimmer and fitter to keep us on the wagon. It *is* rewarding to lose the weight, of course. Unfortunately, time works against us. As the weight comes off, we get hungrier and develop stronger cravings and become more annoyed by the exercise. Meanwhile the weight loss inevitably slows as our metabolism tries to compensate for this deprivation by becoming more parsimonious with calories. Thus, the punishment for sticking to our regimen becomes increasingly severe and constant, and the expected reward recedes into the future. "That gap between the reinforcement of eating and the reinforcement of maybe losing weight months later is a huge challenge," says SungWoo Kahng, a neurobehaviorist who studies obesity at the University of Missouri.

We would be more likely to stick with the regimen if it remained less punishing and more reliably rewarding. Is there a way to make that happen?

FROM BIOLOGY TO BRAIN

THE MOST SUCCESSFUL WAY to date to lose at least modest amounts of weight and keep it off with diet and exercise employs programs that focus on changing behavior. The behavioral approach, tested over decades, involves making many small, sustainable adjustments in eating and exercise habits that are prompted and encouraged by the people and the rest of the environment around us.

The research in support of behavioral weight-loss approaches extends back more than half a century to Harvard University psychologist B. F. Skinner's development of the science of behavioral analysis. The field is founded on the notion that scientists cannot really know what is going on inside a person's brain—after all, even functional MRIs, the state of the art for peering into the mind, are crude, highly interpretable proxies for cognition and emotion that reduce the detailed firing of billions of neurons in complex circuits to a few blobs of color. But researchers can objectively and reproducibly observe and measure physical behavior and the immediate environment in which the behavior occurs, allowing them to identify links between environment and behavior. That typically includes trying to spot events or situations that may be prompting or triggering certain behaviors and noting what may be rewarding and thus reinforcing of some behaviors or punishing and thus inhibiting of others.

The effectiveness of behavioral interventions has been extensively documented for many disorders and problem behaviors. A 2009 meta-analysis in the *Journal of Clinical Child & Adolescent Psychology* concluded that "early intensive behavioral intervention should be an intervention of choice for children with autism." A systematic review sponsored by the U.S. Preventive Services Task Force concluded that even brief behavioral-counseling interventions reduced the number of drinks taken by problem drinkers by 13 to 34 percent for as long as four years. Studies have found behavioral-intervention successes in challenges as diverse as reducing stuttering, increasing athletic performance and improving employee productivity.

To combat obesity, behavioral analysts examine related environmental influences. Which external factors prompt people to overeat or to eat junk food, and which tend to encourage healthful eating? In what situations are the behaviors and comments of others affecting unhealthful eating? What seems to effectively reward eating healthfully over the long term? What reinforces being active? Behaviorally focused studies of obesity and diets as early as the 1960s recognized some basic conditions that seemed correlated with a greater chance of losing weight and keeping it off: rigorously measuring and recording calories, exercise and weight; making modest, gradual changes rather than severe ones; eating balanced diets that go easy on fats and sugar rather than dropping major food groups; setting clear, modest goals; focusing on lifelong habits rather than short-term diets; and especially attending groups where dieters could receive encouragement to stick with their efforts and praise for having done so.

If these strategies today sound like well-worn, commonsense advice, it is because they have been popularized since 1963 by Weight Watchers, which was founded to provide support groups for dieters. Weight Watchers later added other approaches and advice in keeping with the findings of behavioral studies and billed itself as a "behavior-modification" program. "Whatever the details are of how you lose weight, the magic in the sauce is always going to be changing behavior," says Karen Miller-Kovach, former chief science officer of Weight Watchers. "Doing that is a learnable skill."

Studies back the behavioral approach to weight loss. A 2003 review commissioned by the U.S. Department of Health and Human Services found that "counseling and behavioral interventions showed small to moderate degrees of weight loss sustained over at least one year"—a year being an eon in the world of weight loss. An analysis of eight popular weight-loss programs published in 2005 in the *Annals of Internal Medicine* found Weight Watchers (then in its pre-2010 points-overhaul incarnation) to be the only effective program, enabling an average reduction of 3 percent body weight maintained for the two years of the study. Meanwhile a 2005 *JAMA* study found that Weight Watchers, along with the Zone diet (which similarly recommends a balanced diet of protein, carbohydrates and fat), achieved the highest percentage (65 percent) of one-year diet adherence among several popular diets, noting that "adherence level rather than diet type was the key determinant of clinical benefits." A 2010 study in the *Journal of Pediatrics* found that overweight children receiving one year of behavioral therapy dropped 1.9 to 3.3 units more in body mass index, a height-weight relation correlated to body fat, than control subjects did. The *Pediatrics* report noted that "more limited evidence suggests that these improvements can be maintained over the 12 months after the end of treatments."

A 2010 study in *Obesity* found that continuing members of Take Off Pounds Sensibly (TOPS), a national, nonprofit, behaviorally focused weight-loss organization, maintained a weight loss of 5 to 7 percent of their body weight for the three years of the investigation. The U.K.'s Medical Research Council declared in 2010 that its own long-term study had shown that programs based on behavioral principles are more likely to help people take and keep the weight off than other approaches.

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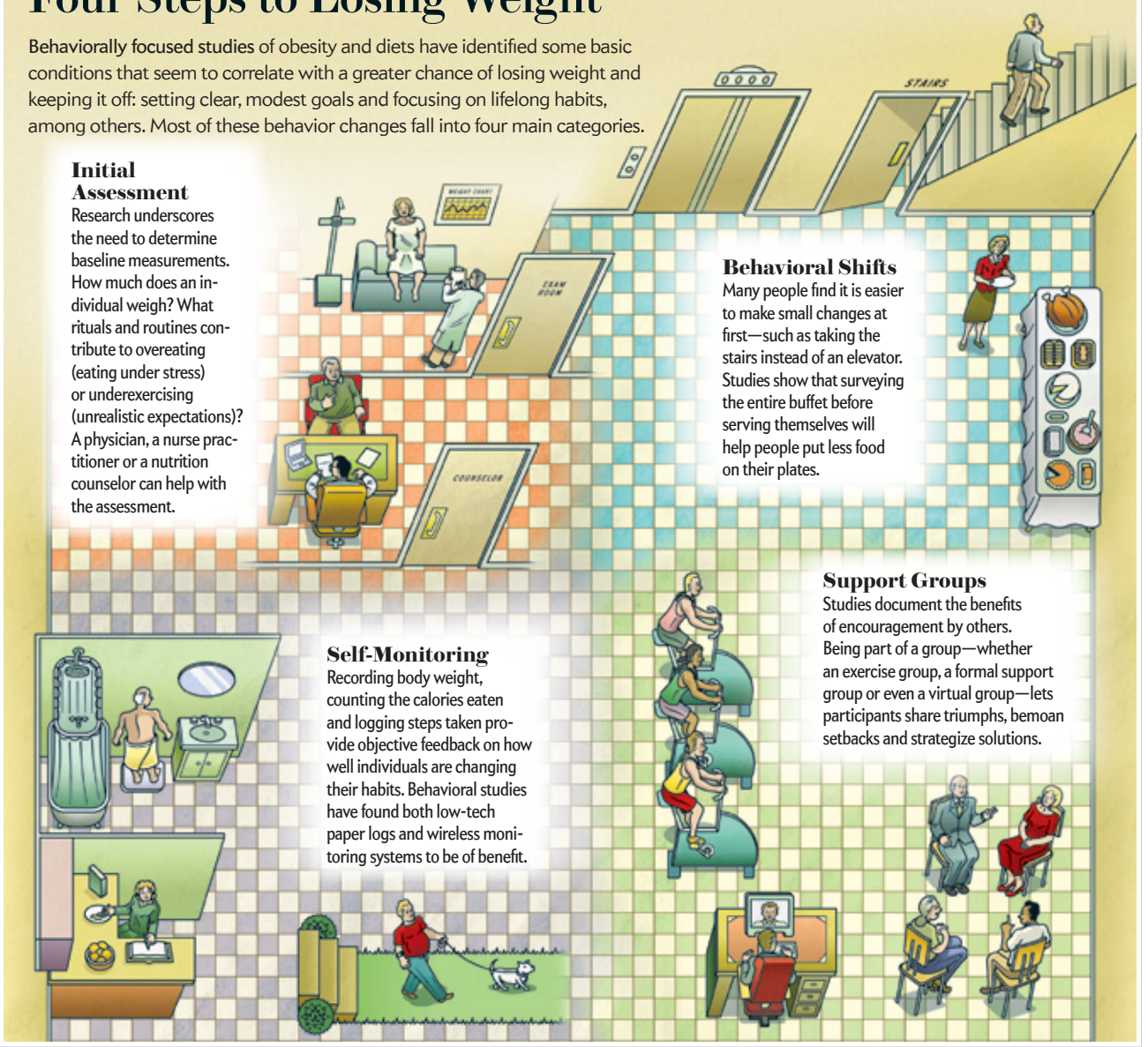
Four Steps to Losing Weight

Behaviorally focused studies of obesity and diets have identified some basic conditions that seem to correlate with a greater chance of losing weight and keeping it off: setting clear, modest goals and focusing on lifelong habits, among others. Most of these behavior changes fall into four main categories.



Initial Assessment

Research underscores the need to determine baseline measurements. How much does an individual weigh? What rituals and routines contribute to overeating (eating under stress) or underexercising (unrealistic expectations)? A physician, a nurse practitioner or a nutrition counselor can help with the assessment.

Behavioral Shifts

Many people find it is easier to make small changes at first—such as taking the stairs instead of an elevator. Studies show that surveying the entire buffet before serving themselves will help people put less food on their plates.

Support Groups

Studies document the benefits of encouragement by others. Being part of a group—whether an exercise group, a formal support group or even a virtual group—lets participants share triumphs, bemoan setbacks and strategize solutions.

Self-Monitoring

Recording body weight, counting the calories eaten and logging steps taken provide objective feedback on how well individuals are changing their habits. Behavioral studies have found both low-tech paper logs and wireless monitoring systems to be of benefit.

(The study was funded by Weight Watchers, but without its participation.)

Weight Watchers and other widely marketed programs tend to fall short, however, in enlisting a full range of behavioral techniques and customizing them to meet the varied needs of individuals. They do not routinely provide individual counseling, adapt their advice to specific challenges, assess environmental factors in a member's home, workplace or community, provide much outreach to members who do not come to meetings, or prevent their members from shooting for fast, dramatic, short-term weight loss or from restricting food groups. In search of profits, Weight Watchers sometimes even mildly panders to these self-defeating notions in its marketing. "Some people join us to drop 10 pounds for a high school reunion," Miller-Kovach says. "They achieve that goal, then stop coming."

To close that gap, a number of researchers have turned their attention in recent years to improving, expanding and tailoring behavioral techniques, with encouraging results. For example, Michael Cameron, chief clinical officer of Pacific Child & Family Associates, a national group of clinics for children with special needs, has authored more than 20 articles in peer-reviewed journals documenting the effectiveness of a wide range of behavioral interventions. A former faculty member at Harvard Medical School's teaching psychiatric hospital, Cameron in 2011 conducted a yearlong, four-person study—behavioral analysts generally do very small group or even single-subject studies to more closely tailor the intervention and observe individual effects—in which the subjects met together with him via online videoconferencing for reinforcement, weighed themselves on scales that transmitted results via wireless networks, and had their diets optimized to both reduce caloric density and address individual food preferences. Favorite foods were used as a reward for exercise. The subjects lost 8 to 20 percent of their body weight, and Cameron says they and the several other people he has worked with outside the study have all kept the weight off.

Matt Normand, a behavioral analyst at

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the University of the Pacific, has investigated ways to more precisely track subjects' calorie intake and expenditure. He collects receipts of their food purchases, provides checklists to record what they eat, and uses pedometers and other devices to measure their physical activity. He then gives participants daily detailed accounts of their calorie flow. In one published study, Normand showed that three of four subjects reduced calorie intake to recommended levels.

Richard Fleming, a researcher at the University of Massachusetts Medical School's Shriver Center, has in *Obesity* looked at ways to encourage parents to steer their children to healthier choices. He has found, among other techniques, that showing parents in person what appropriate serving sizes of foods look like on plates is helpful. Another successful Fleming trick: letting children pick out a small treat at a food store—as long as they walk there. "Kids can really respond to that reward for being active," he says.

Why are behavioral interventions effective? Laurette Dubé, a lifestyle psychology and marketing researcher at McGill University's Faculty of Management, notes that our environment is currently one in which ubiquitous, sophisticated marketing efforts prey on our need for sensory gratification as well as our vulnerability to misinformation. In addition, the poor eating and exercise habits we observe in our friends, family and colleagues encourage us to follow suit. In essence, behavioral interventions seek to reconfigure this environment into one in which our needs for information, gratification and social encouragement are tapped to pull us toward healthy food and exercise choices rather than away from them. "When we are getting the right messages in enough ways, we have a better chance of resisting the urge to eat more than we need," Dubé says.

CHANGING POLICY

THERE IS NO ONE-SIZE-FITS-ALL solution, behavioral or otherwise, to the problem of obesity. But although behavioral interventions work best when they are customized to individuals, mass-market behavioral approaches such as TOPS and Weight Watchers are at least fairly effective. Why don't more people lose weight with them? The main reason is that people simply do not sign up for them, often because would-be weight losers are chasing fad diets or supplements or have read that obesity is locked into our genes. Weight Watchers, by far the most popular behavioral weight-loss program, counts only 600,000 meeting-attending members in its ranks in North America. That means that in the U.S., fewer than one out of 100 obese people and about one out of 200 overweight people are part of a formal behavioral-modification program.

Public policy may be changing, however. The U.S. Surgeon General's office and the CDC have both publicly lined up behind behavioral approaches as the main weapon in what is becoming a war on obesity. First Lady Michelle Obama's Let's Move campaign against childhood obesity consists almost entirely of finding ways to encourage children to eat lower-calorie foods, to become more active, and to enjoy doing it. San Francisco's 2010 ban of free toys in fast-food meals for kids suggests that more officials may be ready to pressure the food industry into easing up on what are essentially obesity-supportive marketing tactics. To encourage people in poorer, disproportionately overweight communities to buy healthier food, the White House has proposed subsidizing the costs of fruits and vegetables.

Approaching the problem from the other direction, former New York City mayor Michael Bloomberg advocated modifying food-assistance programs to restrict the purchase of high-sugar beverages and supported a ban, passed by the city's board of health, on extra-large servings of sugary sodas. In 2014 voters in Berkeley, Calif., approved a surtax of 1 cent per ounce on such drinks. New York City has also offered vouchers for buying produce at farmers' markets to low-income families and incentives to stores to offer healthier fare.

Increasing access to behavior therapy would help, too. Many overweight people might need only online behavioral monitoring, support and progress-sharing tools, which have proved moderately effective in studies. Others may need much more intensive, more personal interventions of the kind Cameron is developing. Given that obesity especially plagues the economically disadvantaged, fees for these programs may have to be heavily subsidized by the government and health care insurers. A weekly session with a behavioral therapist costing $50 would amount to $2,500 a year, or a bit more than a third of the $7,000 a year societal and medical costs of obesity—and the sessions might be needed for only a year or two to establish new, permanent eating and exercise habits, whereas the savings would continue on for a lifetime.

It is too soon to say whether the public will accept government efforts to push it toward healthier choices. San Francisco's ban on Happy Meal toys was initially vetoed by the mayor in response to angry reaction. Efforts by Let's Move to bring healthier food to school cafeterias have been intensely criticized by some as overly intrusive. The courts threw out New York City's ban on large sodas. And voters have rejected taxes on high-calorie beverages in San Francisco and most other cities and states that have proposed them.

Even if such efforts are eventually fully implemented nationwide, there is no way of being sure they will significantly reduce obesity. The current rate of obesity is far beyond any ever seen before on the planet, and thus a large-scale solution will necessarily be an experiment in mass behavior change. But the research suggests that such a grand experiment would be our best shot at fixing obesity and that there is reason to be hopeful it will succeed. Given that more and more scientists, public policy experts and government officials seem eager to get it off the ground, we may well have early findings within this decade. SA

David H. Freedman has been covering science, business and technology for 30 years. His most recent book, *Wrong*, explores the forces that induce scientists and other top experts to mislead us.

MORE TO EXPLORE

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The entry portal to the range of NIH research on obesity: **obesityresearch.nih.gov**

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SECURITY

IS YOUR FOOD CONTAMINATED?

New approaches are needed to protect the food supply

By Mark Fischetti

GIVEN THE BILLIONS OF FOOD ITEMS THAT ARE PACKAGED, PURCHASED AND CONSUMED every day in the U.S., let alone the world, it is remarkable how few of them are contaminated. Yet since the terrorist attacks of September 11, 2001, "food defense" experts have grown increasingly worried that extremists might try to poison the food supply, either to kill people or to cripple the economy by undermining public confidence. At the same time, production of edible products is becoming ever more centralized, speeding the spread of contaminants—natural ones or those introduced purposely—from farms or processing plants to dinner tables everywhere. Mounting imports pose yet another rising risk.

Can we protect food from tainting? And if toxic substances or pathogens do slip into the supply chain, can they be quickly detected to limit their harm to consumers? Tighter production procedures can go a long way toward protecting the public, and if they fail, smarter monitoring technologies can at least limit injury.

TIGHTEN SECURITY

PREVENTING A TERRORIST or a disgruntled employee from contaminating milk, juice, produce, meat or any other type of comestible is a daunting problem. The food supply chain comprises a maze of steps, and virtually every one of them presents an opportunity for tampering. Blanket solutions are unlikely to work because "the chain differs from commodity to commodity," says David Hennessy, an economics professor at Iowa State University's Center for Agricultural and Rural Development. "Protecting dairy products is different from protecting apple juice, which is different from protecting beef."

IN BRIEF

Terrorist plots, greater imports and more centralized food production are raising the chances that food will be tainted by natural or man-made contaminants.

Safety procedures adapted from military methods of vulnerability analysis can tighten the physical security of food-production facilities.

New technologies such as microfluidic chips, RFID tags and edible markers can detect contamination, help trace it back to its source and speed recalls.

Streamlining government regulations could help, but closer oversight by brand-name sellers of their suppliers will do more to ensure safer fare.

Photograph by Aaron Goodman

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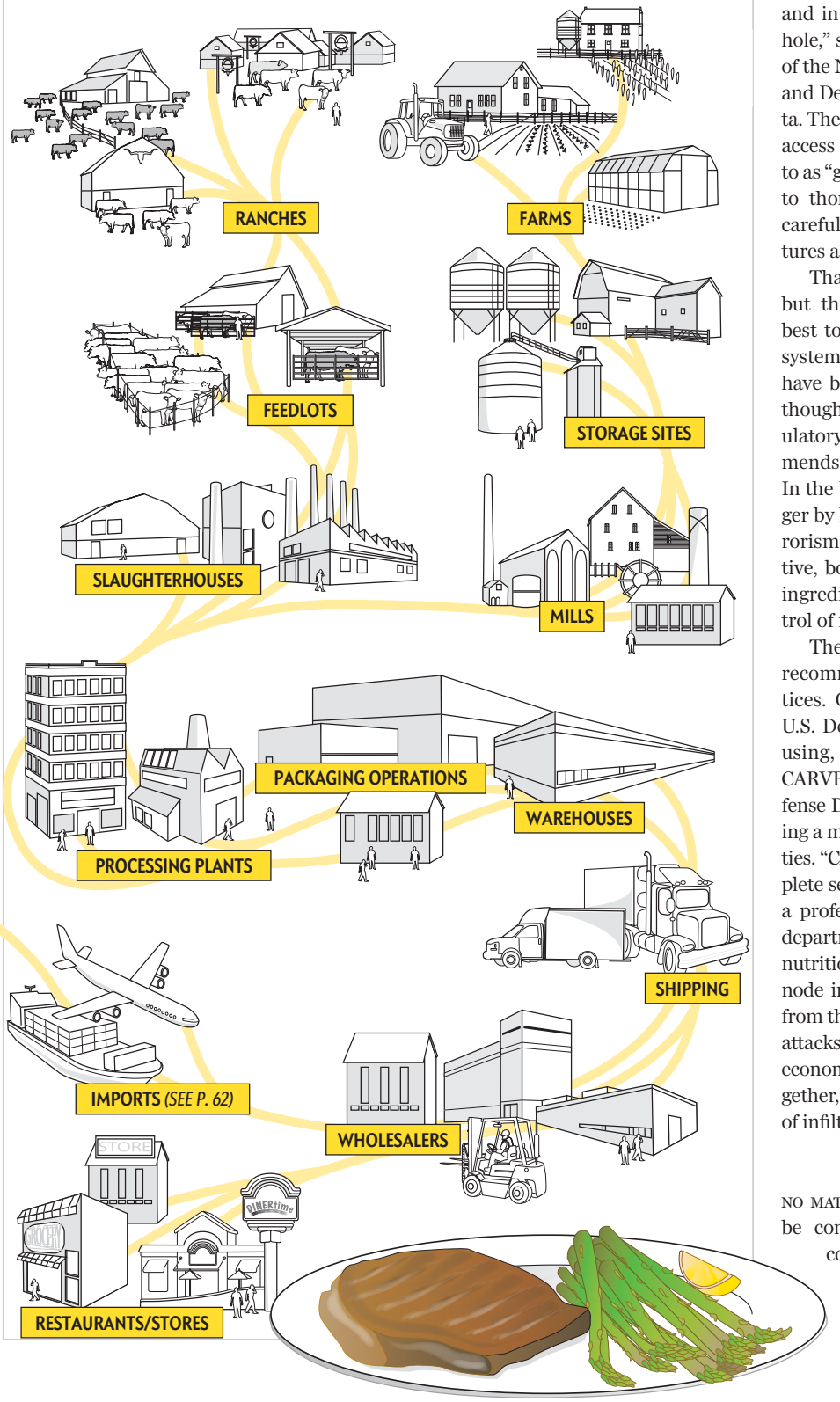
THE PROBLEM

Vulnerabilities Everywhere

The food supply chain includes numerous steps where natural pathogens can multiply or where terrorists or disgruntled employees could introduce toxic substances. The main countermeasures are to impose tight security and production procedures at each facility.



Even within a given supply chain, technology offers few quick fixes. Preventing contamination largely comes down to tightening physical plant security and processing procedures at every turn. Each farmer, rancher, processor, packager, shipper, wholesaler and retailer "has to identify every possible vulnerability in the facility and in its procedures and close up every hole," says Frank Busta, director emeritus of the National Center for Food Protection and Defense at the University of Minnesota. The effort begins with standard facility access controls, which Busta often refers to as "gates, guns and guards," but extends to thoroughly screening employees and carefully sampling products at all junctures across the facility at all times.

That advice seems sound, of course, but the challenge for operators is how best to button down procedures. Several systems for safeguarding food production have been rolled out in recent years. Although these are not required by any regulatory agency, Busta strongly recommends that producers implement them. In the U.S., that impetus was made stronger by legislation such as the 2002 Bioterrorism Act and a 2004 presidential directive, both of which enhanced scrutiny of ingredient suppliers and tightened control of manufacturing procedures.

The primary safeguard systems Busta recommends borrow from military practices. One tool, which the FDA and the U.S. Department of Agriculture are now using, carries the awkward name of CARVER+Shock. It was adapted from Defense Department procedures for identifying a military service's greatest vulnerabilities. "CARVER+Shock is essentially a complete security audit," says Keith Schneider, a professor at the University of Florida's department of food science and human nutrition. The approach analyzes every node in the system for factors that range from the likely success of different kinds of attacks to the magnitude of public health, economic and psychological effects (together, the "shock" value) that a given type of infiltration could cause.

TRACK CONTAMINANTS

NO MATTER how tightly procedures might be controlled, determined perpetrators could still find ways to introduce pathogens or poisons. And natural pathogens such as *Salmonella* are always a concern. Detect-

Illustrations by Lucy Reading-Ikkanda

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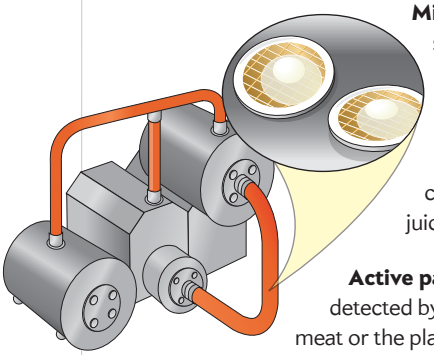
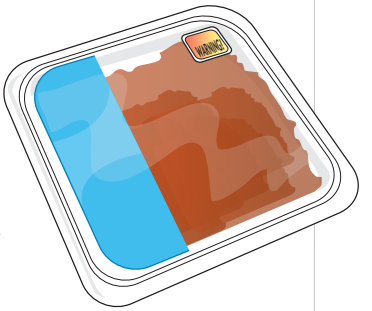
COMING TECHNOLOGIES

Detect, Track and Trace

When a natural pathogen, or a perpetrator, contaminates food, lives can be saved if the tainting can be quickly detected and traced to its origin, so that the rest of the batch can be destroyed or recalled. Several technologies, in various stages of development, could help:

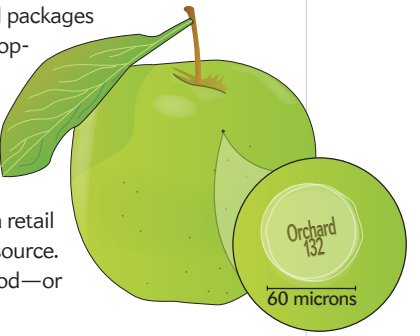


Microfluidic detectors—Botulinum bacteria produce the most poisonous toxin known. They and similar agents, such as *Escherichia coli*, could be detected during food processing by microfluidic chips—self-contained diagnostic labs the size of a finger. Research groups have crafted chips in which channels are lined with antibodies that can detect botulism or *E. coli* during milk production. Samples could be tested either before or after the milk is piped into tanker trucks that leave the dairy and again before or after it is pasteurized at a production plant. Similar chips could detect other toxic substances at fluid-processing plants that produce apple juice, soup, baby formula and other liquid foods.



Active packaging—*E. coli, Salmonella* and other pathogens could be detected by small windows in packaging, such as the cellophane around meat or the plastic jar around peanut butter. The "intelligent" window would contain antibodies that bind to enzymes or metabolites produced by the microorganism; if binding occurred, the patch would turn color. The challenge is to craft the windows from materials and reactants that can safely contact food. Similar biosensors could react if the contents reached a certain pH level or were exposed to high temperature, indicating spoilage. And they could sense if packaging was tampered with, for example, by reacting to the pressure imposed by a syringe or to oxygen seeping in through a puncture hole.

RFID tags—Pallets or cases of a few select foods now sport radio-frequency identification (RFID) tags that, when read by a scanner, indicate which farm or processing plant the batch came from. Future tokens that are smaller, smarter and cheaper could adorn individual packages and log every facility they had passed through and when. Researchers have been developing tags that could be read through fluid (traditional designs cannot) and thus could be embedded inside the wall of sour cream or yogurt containers. Active tags could record the temperatures a package had been exposed to, but they are more expensive to produce.



Edible tags—Manufacturers often combine crops from many growers, such as spinach leaves, into a retail package, so tags affixed to bags might not help investigators track contamination back to a specific source. Edible inks can now be used to print markers that indicate site of origin directly onto a package of food—or in some cases, onto the food itself.

ing these agents, tracing them back to the spot of introduction, and tracking which grocery stores and restaurants ended up with tainted products are paramount. Putting such systems in place "is just as important as prevention," Schneider says.

Here new technology does play a major role, with various sensors applied at different points along the chain. "You can't expect one technology to counter all the possible taintings for a given food," notes Ken Lee, former director of Ohio State University's department of food science and technology.

A variety of hardware is being developed [*see box above*], although little has been deployed commercially thus far. Radio-frequency identification (RFID) tags are furthest along, in part because the Defense Department and Walmart have required their main suppliers to attach the tokens to pallets or cases of foodstuffs. The Metro AG supermarket chain in Germany has done the same. The ultimate intent is for automated readers to scan the tags at each step along the supply chain—from farm, orchard, ranch or processor, through packaging, shipping and wholesale—and to report each item's location to a central registry. That way if a problem surfaces, investigators can quickly determine where the batch originated and which stores or facilities might have received goods from that batch and when. Retailers can also read the tags on their items to see whether they received a product that was later identified as suspicious.

As RFID tags get smaller and cheaper, they may be placed directly on individual items—on every bag of spinach, jar of peanut butter, container of shrimp and sack of dog food. "That way if a recall is issued, the items can be found as they run past a scanner at the checkout counter," says Jean-Pierre Émond, of the electro-optical systems laboratory at the Georgia Tech Research Institute.

Universities and companies are developing all kinds of other tags, some that are very inexpensive and others that cost more but supply extensive information. Some tokens, for example, can sense

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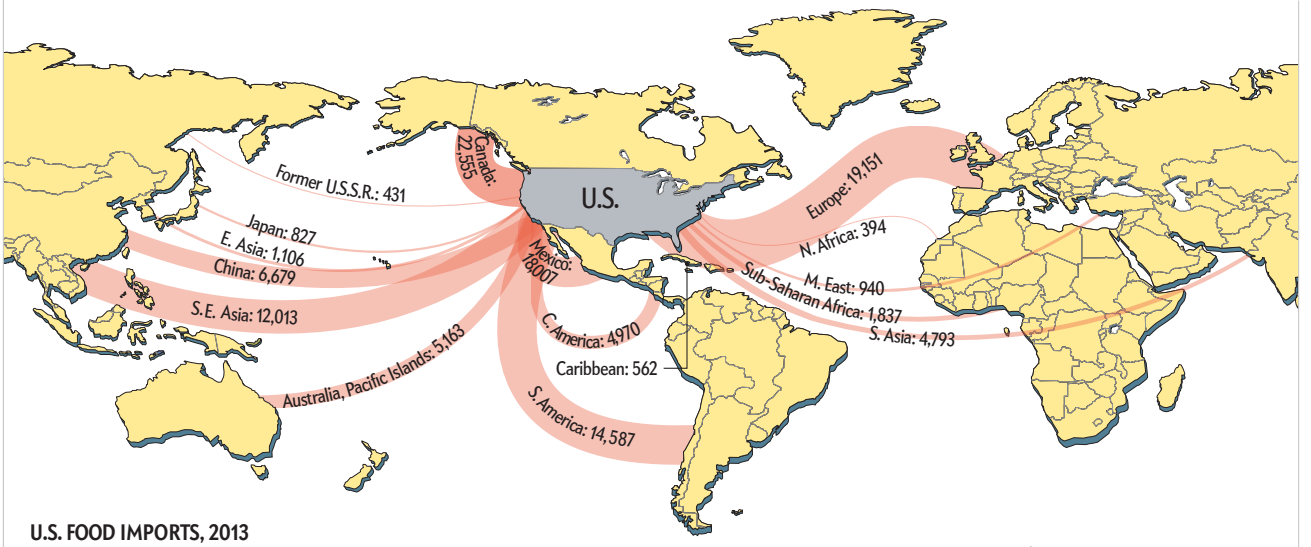
Making Imports Safer

Regardless of how safe domestic food production is, imports are our Achilles' heel. Realistically, no technology can ensure that imports are safe. The food in every shipping container entering a U.S. port or border crossing could be pulled and irradiated, and some comestibles such as spices are already processed this way. But industry experts say the step would add significant costs for producers and shipping delays for middlemen. And the public continues to be wary of the technology. Furthermore, although irradiation would kill pathogens, it would have no effect on poisons or adulterants.

Inspecting all incoming food would require vast increases in FDA and U.S. Department of Agriculture budgets; the agencies currently inspect a meager 1 percent of imports. But a 2011 law, the Food Safety Modernization Act, mandates that this will soon change. The FDA is now finalizing rules that, when they go into effect in 2016 and 2017, will overhaul its food safety program, including its protection against tainted imports. The agency says it has already started ramping up inspection of food-export facilities and now looks at about 1,200 a year. But the law requires it to set up a verification system for foreign food suppliers—which includes more than 100,000 facilities—that will require importers and U.S. manufacturers that use imported ingredients to provide safety plans that include more detailed information about production processes at foreign suppliers.

The best recourse, Lee says, is for companies to insist that suppliers impose strict standards and that the companies send inspectors overseas to verify compliance. Other experts agree, adding that government edicts are not as effective. "Too often import requirements are used as trade barriers, and they just escalate," says David Hennessy, an economics professor at Iowa State University. "The food companies themselves have a lot to lose, however. When they source a product in a country, they ought to impose tough procedures there." —*M.F.*



SOURCE: U.S. DEPARTMENT OF AGRICULTURE

whether food has been exposed to warm temperatures and thus might be more likely to harbor *Escherichia coli* or *Salmonella* bacteria. Other tags could track how long items spent in transit from node to node in the supply chain, which could indicate unusually long delays that might raise suspicion about tampering. So-called active packaging could detect contamination directly and warn consumers not to eat the product they are holding.

The big impediment for any marker, of course, is the price. Today it costs around 15 cents to put an RFID tag on a case of lettuce. For some growers, Émond notes, that could equal the profit they are going to make on that case. To be embraced widely, therefore, he says tags will have to provide additional value to suppliers or buyers.

The University of Florida conducted a project with Publix Super Markets and produce suppliers in Florida and California to assess such possibilities. In initial trials, tags tracked crates and pallets that were shipped from the growers to several of Publix's distribution centers. Information gleaned from scanning tags at various points was available to all the companies via a secure Internet site hosted by VeriSign, the data security firm. The compilation allowed the participants to more quickly resolve order discrepancies, to log how long food sat idle and to reveal ways to raise shipping efficiency.

CONTROL SUPPLIERS

COSTS WILL NOT DROP until new technologies are deployed widely. But food defense analysts say adoption is unlikely to occur until clear, streamlined regulations are enacted. And that prospect, in turn, seems likely to be remote until the high-

Illustration by George Retseck and Lucy Reading-Ikkanda

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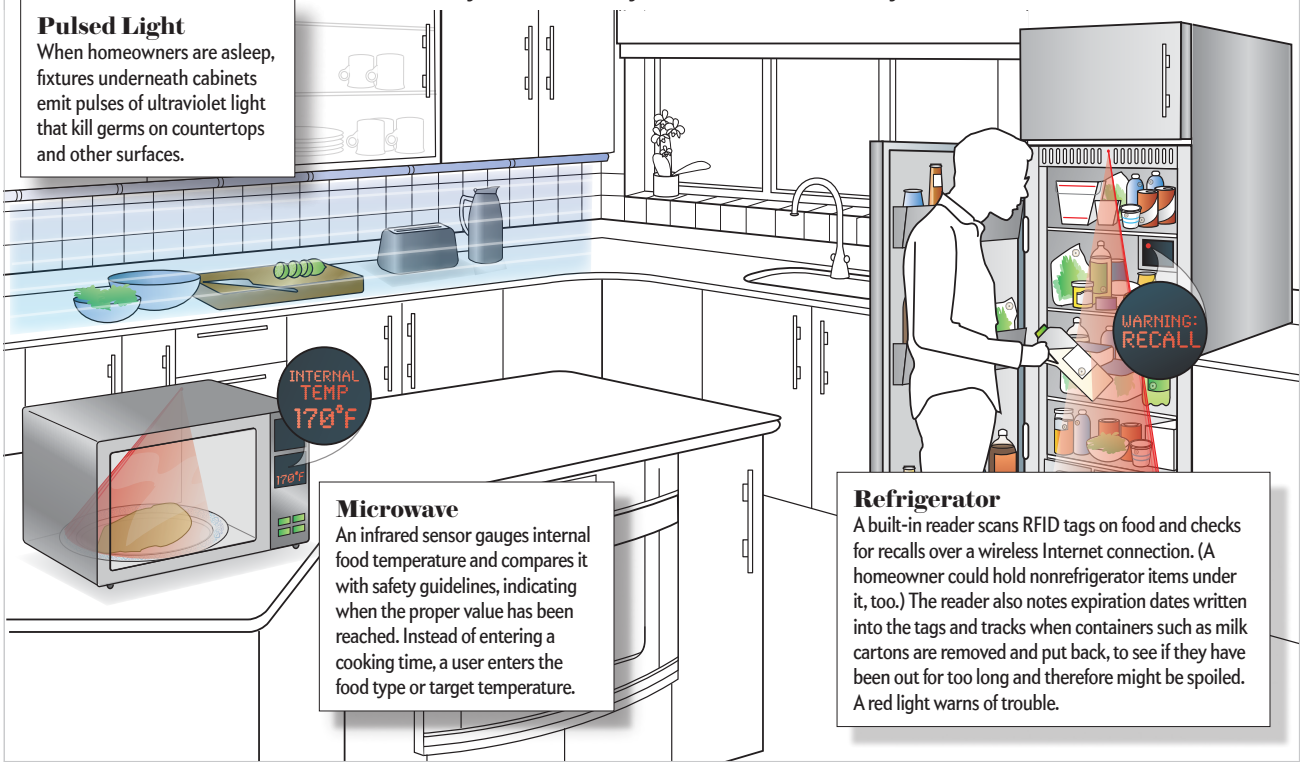
The Vigilant Kitchen

If contaminated food does make it into your grocery bag, smart appliances could still prevent it from reaching your mouth. Innovations that could reach commercial introduction are described here by Ken Lee of Ohio State University. "None of this technology would be visually obtrusive," he says, "and all of it would be easy to clean."


Pulsed Light
When homeowners are asleep, fixtures underneath cabinets emit pulses of ultraviolet light that kill germs on countertops and other surfaces.
INTERNAL TEMP 170°F
170°F
Microwave
An infrared sensor gauges internal food temperature and compares it with safety guidelines, indicating when the proper value has been reached. Instead of entering a cooking time, a user enters the food type or target temperature.
WARNING: RECALL
Refrigerator
A built-in reader scans RFID tags on food and checks for recalls over a wireless Internet connection. (A homeowner could hold nonrefrigerator items under it, too.) The reader also notes expiration dates written into the tags and tracks when containers such as milk cartons are removed and put back, to see if they have been out for too long and therefore might be spoiled. A red light warns of trouble.

est levels of government are reformed.

"There are more than a dozen different federal agencies that oversee some aspect of food safety," Lee points out, noting that simple coordination among them is difficult enough, and efficient approval of sensible requirements is even harder to come by. The FDA regulates pizza with cheese on it, but the USDA regulates pizza if it has meat on it, quips Jacqueline Fletcher, a professor of entomology and plant pathology at Oklahoma State University. "The requirements for organic farmers are different from those for nonorganic farmers."

Spurred by recalls and outbreaks, Congress passed the Food Safety Modernization Act in 2011, which directed the FDA to refocus its efforts on prevention of contamination rather than recalls of bad food, strengthen inspections of both domestically produced and imported foods [*see box on opposite page*], and make better use of risk analysis in setting its priorities. In February, the Obama administration proposed unifying responsibility for prevention of food contamination and response to outbreaks of foodborne illness in a new Food Safety Administration.

More effective government is good, but experts say food suppliers also need to improve vigilance. "The strongest tool for stopping intentional contamination is supply-chain verification," says Shaun Kennedy, director of the National Center for Food Protection and Defense. Each brand-name provider such as Dole and each grocery store conglomerate such as Safeway must verify that every company involved in its supply chain implements the latest security procedures and detection, track and trace technologies—and drop those that do not.

Brand-name providers, after all, have the most to lose. If a natural or man-made toxin is found in, say, a bag of Dole spinach or a container of Safeway milk, consumers will shun that particular label. "If a brand-name company wants to protect its products," Kennedy says, "it should validate every participant in the chain, all the way back to the farm." SA

Mark Fischetti is a senior editor at *Scientific American*.

MORE TO EXPLORE

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The Case of Botulinum Toxin in Milk: Experimental Data. Oliver G. Weingart et al. in *Applied and Environmental Microbiology*, Vol. 76, No. 10, pages 3293–3300; May 2010.
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National Center for Food Protection and Defense: www.ncfpd.umn.edu

scientificamerican.com/magazine/sa

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HISTORY

THE BIRTH OF THE MODERN DIET

Ever wonder why dessert is served after dinner? The origins of modern Western cooking can be traced to ideas about diet and nutrition that arose during the 17th century

By Rachel Laudan

WERE WE TO ATTEND A 16TH-CENTURY COURT BANQUET in France or England, the food would seem strange indeed to anyone accustomed to traditional Western cooking. Dishes might include blancmange—a thick puree of rice and chicken moistened with milk from ground almonds and then sprinkled with sugar and fried pork fat. Roast suckling pig might be accompanied by a cameline sauce, a side dish made of sour grape juice thickened with bread crumbs, ground raisins and crushed almonds and spiced with cinnamon and cloves. Other offerings might include fava beans cooked in meat stock and sprinkled with chopped mint—or quince paste, a sweetmeat of quinces and sugar or honey. To wash it all down, we would probably drink hypocras, a mulled red wine seasoned with ground ginger, cinnamon, cloves and sugar.

Sumptuous spread from the 16th century might have included blancmange (a puree of rice and chicken) and a side dish of cameline sauce (made of crushed almonds, bread crumbs and spices moistened with sour grape juice), accompanied by mulled red wine, or hypocras. By the 17th century, the foods looked more familiar to the modern eye: roast turkey, green salad with oil and vinegar dressing, and sparkling white wine.

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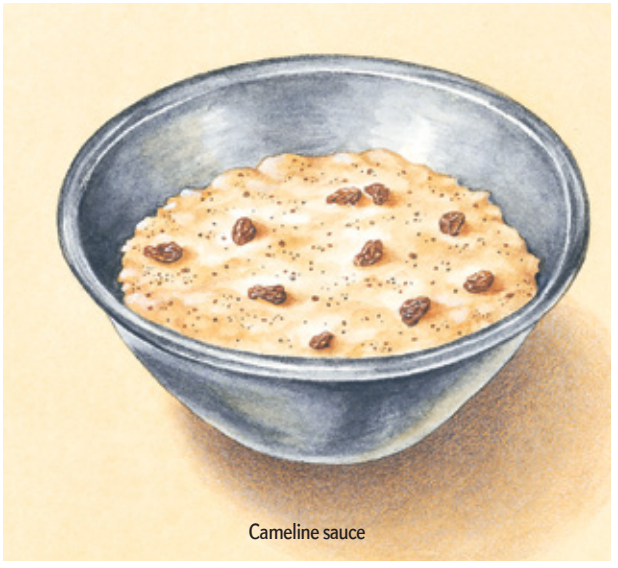
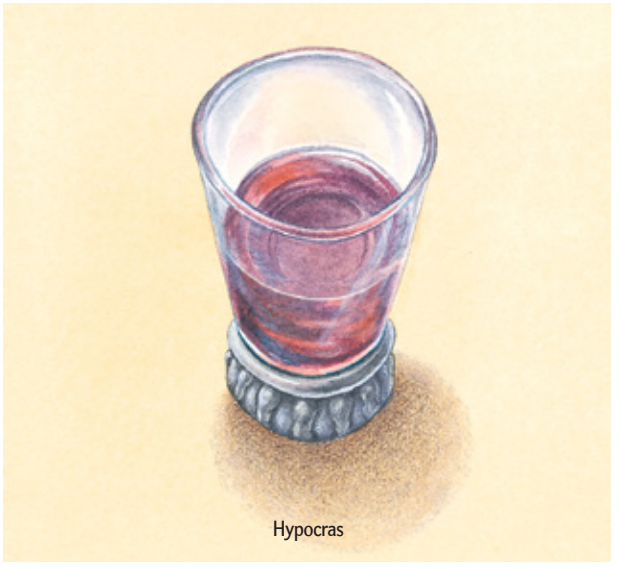
BEFORE 1650

Blancmange

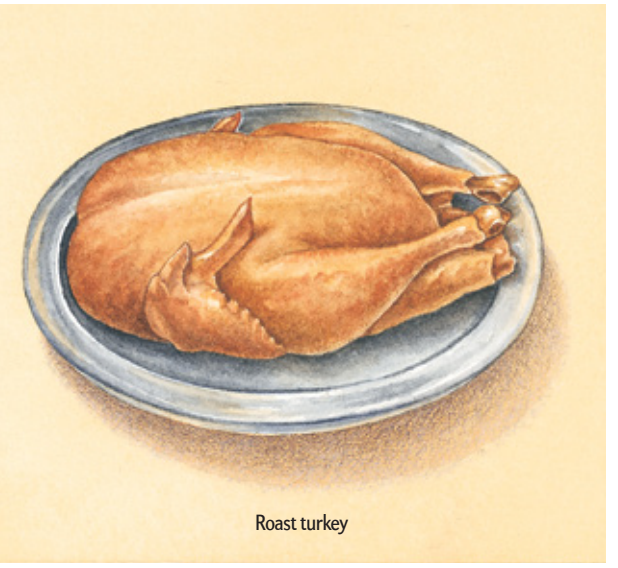


Cameline sauce



Hypocras

AFTER 1650



Roast turkey

Salad

Sparkling wine

HEIDI NOLAND

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Fast-forward 100 years, however, and the food would be reassuringly familiar. On the table in the late 1600s might be beef bouillon, oysters, anchovies and a roast turkey with gravy. These dishes might be served alongside mushrooms cooked in cream and parsley, a green salad with a dressing of oil and vinegar, fresh pears, lemon sherbet, and even cool, sparkling white wine.

Before 1650, the elite classes throughout the Islamic and Christian worlds from Delhi to London shared pretty much the same diet: thick purees, lots of spices, sweet and sour sauces, cooked vegetables, warmed wine, and of course bread—white, raised breads in the West and mainly flat breads in northern India and the Middle East. Sugar was ubiquitous as a seasoning in savory dishes.

But in the middle of the 17th century, the northern European diet began to change. This new regimen relied on fewer spices, based its sauces on fats such as butter and olive oil, and incorporated raw fruits and vegetables. Sugar appeared only at the end of a meal.

What happened? Economic considerations cannot account for the difference: for the upper class, money was no object. For the poor, both meals would have been far out of reach. Well into the 19th century, those in the lower economic classes subsisted on vegetable soups and gruels with bread or porridge. Novel foodstuffs from the New World do not explain the shift in diet either, because with the exception of turkey, the dishes at the second banquet depended not on new ingredients but on new uses of long familiar ones. The clue to this transformation in eating habits between the 16th and 17th centuries must be sought instead in evolving ideas about diet and nutrition—which is to say, in the history of chemistry and medicine.

MEDICINE IN THE 16TH CENTURY

EATING HEALTHY FOOD was extremely important to people of earlier eras, perhaps even more so than it is today. Activity in the kitchen mattered so much because physicians had so few other options. To avoid resorting to unpleasant therapies such as purging or bloodletting, doctors carefully monitored their wealthy patients' daily habits: their emotional state, for example, or how much sleep, exercise and fresh air they got. Most crucially, doctors advised their patients on the food and drink they should consume.

EATING HEALTHY FOOD WAS EXTREMELY IMPORTANT TO PEOPLE OF EARLIER ERAS, PERHAPS EVEN MORE SO THAN IT IS TODAY.

Every court had a bevy of physicians who were schooled in the physiology of human digestion, the nutritive properties of foodstuffs and the nature of a healthy meal. Offering dietary advice to their affluent patrons was a major part of their work.

The actual task of transforming abstract dietary theory into dishes appropriate for the courtly table fell to the master cooks, as executive chefs were then called. In a popular medical text written in 1547, *Breviary of Health,* author Andrew Boorde noted, "A good coke is halfe a physycyon."

Sixteenth-century cooks, physicians and their patrons shared a common notion of diet and nutrition that can be traced to classical antiquity. First formulated around 400 B.C. as part of the Hippocratic Collection, the ideas were systematized by the great Roman doctor Galen in the early second century A.D. After the collapse of classical civilization, Islamic intellectuals eagerly took up these beliefs (along with many other scientific theories of the ancient world). By the 12th century, European scholars had translated key Arabic texts into Latin; teachers at the major medical schools, such as Montpellier in the south of France, relied extensively on these texts. In the late 15th century, experts began translating newly discovered Greek manuscripts as well as retranslating known texts.

These documents formed the basis of a host of popular manuals and mnemonic jingles. Particularly well liked were the numerous vernacular variations on a Latin poem, the *Regimen Sanitatis Salernitanum,* which was apparently composed around the end of the 11th century but still widely circulated in the 16th and even 17th centuries:

Peaches, apples, pears, milk,
cheese, and salted meat,
Deer, hare, goat, and veal,
These engender black bile and are
enemies of the sick

The prevailing dietary wisdom of the 16th century, as presented in these medical guidebooks, relied on two assumptions. The first axiom was that the process of digesting foods was actually a form of cooking. Indeed, cooking stood as the basic metaphor for the systems that sustained all life. Seeds were "cooked" into plants; when the plants appeared above the ground, the heat of the sun cooked them into ripe fruits and grains. If humans gathered these foodstuffs, they could cook them further to create edible dishes. Finally, the internal heat of the body turned the food into blood. The body then expelled as feces what was not digestible. Excrement joined putrefying dead animals and plants to begin the life cycle again.

The second assumption underlying

IN BRIEF

As ideas about digestion evolved over the centuries, so have the menus served to the wealthy of the West.
In the 16th century, digestion was believed to be a form of cooking. Foods were associated with combinations of the four Aristotelian elements: air, water, fire and earth. The perfect meal, according to this dietary philosophy, was slightly warm and slightly moist.
By the 17th century, physicians and chefs thought of digestion as a form of fermentation. Elites favored fat-based sauces, salt and fresh produce, and they relegated sugar to dessert.
By the late 20th century, almost all Westerners could afford a rich person's diet of the 17th century, but research in physiology and nutrition had led to further shifts in the view of healthy food.

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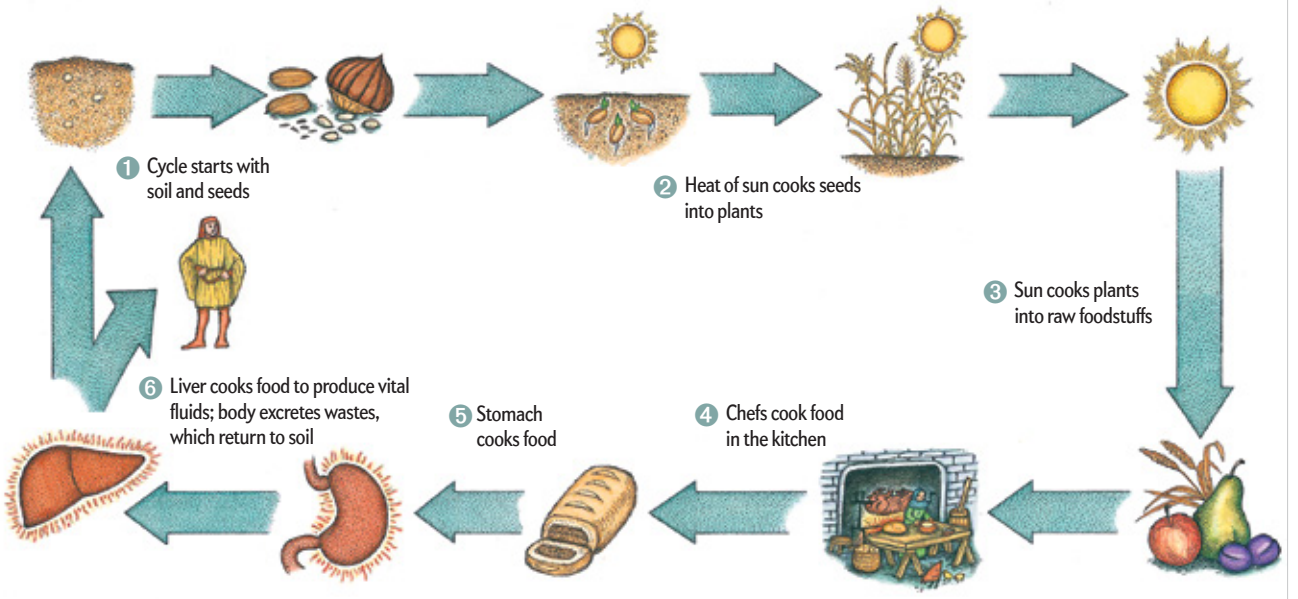
UNIFYING PRINCIPLE

The Cosmic Culinary Cycle before 1650

… in which cooking was believed to be the central process of life.


1 Cycle starts with soil and seeds
2 Heat of sun cooks seeds into plants
3 Sun cooks plants into raw foodstuffs
4 Chefs cook food in the kitchen
5 Stomach cooks food
6 Liver cooks food to produce vital fluids; body excretes wastes, which return to soil

16th-century medical advice was that eating a suitably balanced diet helped to maintain a proper equilibrium of bodily fluids. Doctors and chefs of the time believed that four fluids, or humors, circulated in the body: blood, phlegm, yellow bile and black bile. These humors corresponded to the four Aristotelian elements—air, water, fire and earth. Blood, being hot and moist, was analogous to air. Phlegm was cold and moist and therefore resembled water. Yellow bile was hot and dry, similar to fire, whereas black bile was cold, dry and thus connected to earth.

In this theory, a human body in perfect health was slightly warm and slightly moist, although in practice the exact balance varied from individual to individual, depending on variables such as age, sex and geographic location. Older people were thought to be colder and drier than younger ones; menstruating women colder and wetter than men; southern Europeans hot-blooded compared with their neighbors to the north.

The perfect meal, like the perfect human temperament, was thought to be slightly warm and slightly moist. But combinations away from this center could be used as mild dietary correctives to warm and moisten the elderly, dry out the moister sex, and calm down the southerner or perk up the northerner.

The master cook, then, had the challenge of selecting and preparing meals adjusted to the temperament of the eater. The properties of any given food item were common knowledge: pepper, for example, was hot and dry in the third degree, and vinegar was cold and wet in the second degree. Root vegetables such as turnips were by nature earthy—dry and cold—and thus better left to peasants. If chefs should decide to prepare them, however, they would make sure to stew them to add warmth and moisture. In contrast, chard, marrow (a watery, squashlike vegetable) and especially onions were very wet and had to be fried.

THE PERFECT MEAL WAS THOUGHT TO BE SLIGHTLY WARM AND SLIGHTLY MOIST—BUT DIETARY CORRECTIVES COULD WARM THE ELDERLY, DRY OUT THE MOISTER SEX, AND CALM HOT-BLOODED SOUTHERNERS.

Certain foods were deemed completely unacceptable: Guy Patin, a doctor at the University of Paris and author of *Treatise on the Conservation of Health,* published in 1632, cautioned that mushrooms, being cold and wet, should be avoided entirely. Melons and other fresh fruit were not much better, being very moist and liable to putrefy. In general, though, cooking not only helped achieve proper culinary balance—dry foods were boiled, wet foods fried or roasted—but the process also, in effect, partially predigested the foods, thus making them easier for the body to assimilate.

According to these medical theories, the blancmange on our 16th-century table was close to perfect. The wise chef had combined chicken, rice and almond milk, all slightly warm and moist, and

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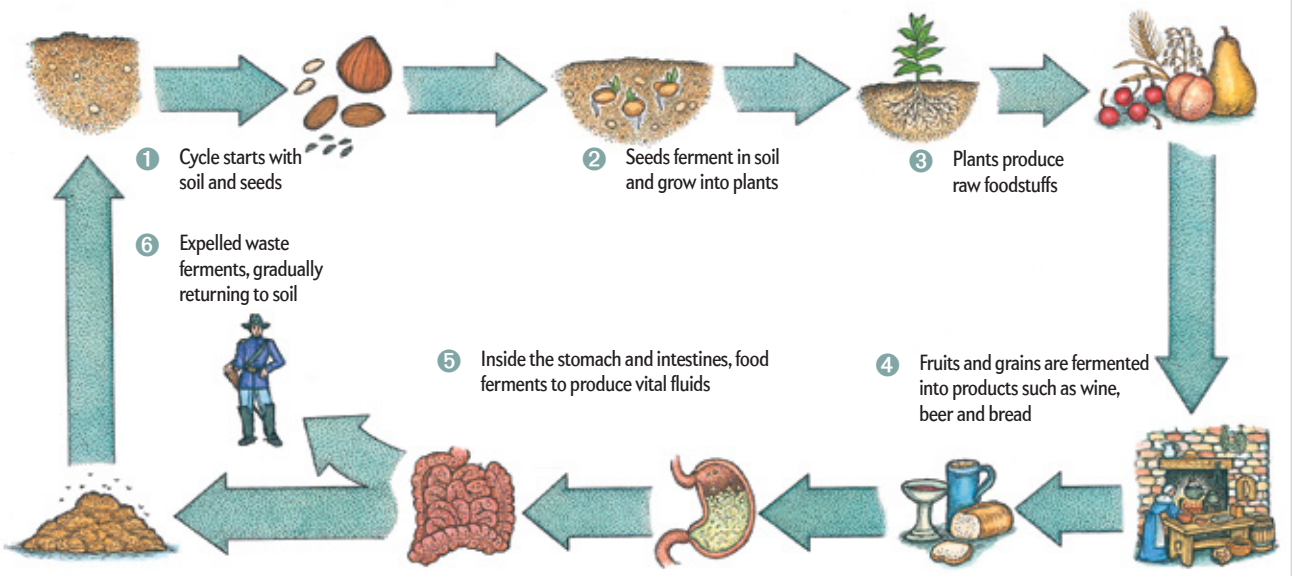
The Cosmic Culinary Cycle after 1650

… in which fermentation was believed to be the central process of life.


1 Cycle starts with soil and seeds
2 Seeds ferment in soil and grow into plants
3 Plants produce raw foodstuffs
4 Fruits and grains are fermented into products such as wine, beer and bread
5 Inside the stomach and intestines, food ferments to produce vital fluids
6 Expelled waste ferments, gradually returning to soil

the sugar on top—also warm and moist—was the crowning touch. The naturally moist suckling pig had been roasted. The cameline sauce balanced cool, moist vinegar with the warmth of raisins and hot, dry spices. The chef was careful not to serve quinces and grapes fresh, and hence dangerously cold and moist, but instead offered them dried or cooked with added sugar (in the quince paste).

Health experts approved of wine served with a meal, viewing it as an ideal nutrient—provided, of course, that diners did not drink to excess. *The Book of Wine,* written around 1310, printed in 1478 and widely attributed to Arnald of Villanova (a leading medical writer and physician to King James II of Aragon), had only high praise for the beverage. Wine is not only good for flatulence and infertility, the book asserts, but it also "fortifies the brain and the natural strength … causes foods to be digested and produces good blood."

Even so, because red wine tended to be cold and dry, chefs often served it warm with added sugar and spices, creating hypocras. With these options before them, the members of the 16th-century court could rest assured that they were getting a healthy meal.

17TH-CENTURY COOKING

BY THE MIDDLE of the 17th century, however, physicians of a quite different persuasion began to join the courts of northern Europe. These scholars derived their ideas from Paracelsus, an itinerant doctor from Germany who, in the 1520s, began to mock the structure of classical medicine. Paracelsus's abrasive personality and radical religious beliefs gave him a dreadful reputation, so few physicians admitted to this heritage. But acknowledged or not, the link was clear: these court doctors argued, as Paracelsus had, that the idea of a cosmic life cycle based on cooking and the Aristotelian elements was wrong and had to be revised.

17TH-CENTURY CHEMISTS PROPOSED THREE NEW ELEMENTS—MERCURY, SULFUR AND SALT—TO REPLACE ARISTOTLE'S FOUR.

Historians of science still debate the causes of this shift, but the technology of distillation seems to have contributed to it. As the practice became more important from the late Middle Ages on, chemists experimented with heating a great variety of natural substances, many of them edible, such as fennel, nutmeg and cloves. They noted that in every case the original material separated into three parts: a volatile, or "spirituous," fluid; an oily substance; and a solid residue.

Drawing on such observations, these chemists proposed three new elements in place of Aristotle's four: mercury, sulfur and salt. Although each of these is familiar to us today as a common element or compound, the early chemists used the terms to connote things quite unrelated to a specific liquid metal, yellow powder or white crystal. Mercury was considered to be the essence of the vaporous fluids, sulfur was the essence of the oily substances, and salt was the essence of all solids.

In such a scheme, salt dictated the taste and consistency of foods. Mercury

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was the source of smells and aromas. Sulfur, or oil, carried the properties of moistness and sweetness; it also bound together the other two, usually antagonistic, elements.

Physicians of this era also believed that human digestion involved fermentation rather than cooking, and they began to investigate the familiar yet mysterious process more closely. Because fermentation included gentle heat and the production of vapors, it seemed to resemble (or was possibly the same as) putrefaction, distillation, and the interaction of acids and salts. Vapors, spirits or airs (soon to be dubbed "gases" by Dutch scientist and mystic Johannes Baptista van Helmont) excited chemists of the time, as they appeared to be the very essences of the substances from which they originated.

Several prominent physicians of the 17th century advocated this new understanding of digestion as a kind of fermentation, among them van Helmont, Franciscus Sylvius, a physician at the University of Leiden, and Thomas Willis, then the best-known doctor in England and a founding member of the Royal Society of London. According to this view, gastric juices, considered acid and sharp, acted on foods to turn them into a white, milky fluid, which then mixed with alkaline bile in the digestive tract. The mixture fermented and bubbled, producing a salty substance that the body could transform into blood and other fluids.

Like their 16th-century predecessors, these later physicians presented a cosmic cycle of life that reflected their view of digestion. Seeds became plants as a result of the "ferments of the earth," in the words of John Evelyn, a keen horticulturist who spoke before the Royal Society in 1675. Fermentation turned grains and fruits into bread, beer and wine, which the digestive system could ferment further. Putrefaction of waste material started the cycle all over again.

"Vegetable putrefaction resembles very much Animal Digestion," wrote John Arbuthnot, member of the Royal Society and physician to Queen Anne, in a popular handbook on foodstuffs that appeared in 1732. The cosmos was still a kitchen but was now equipped with brewers' vats, and the human body held miniature copies of that equipment.

These changes in the understanding of the digestive process put 17th-century chefs on guard. Alert cooks seized the opportunity to establish their good reputations by thinking up dishes that were healthful by the new standards—and, of course, also tasty. For instance, chefs welcomed oysters, anchovies, green vegetables, mushrooms and fruits because they fermented so readily and thus did not need complicated preparation in the kitchen to be predigested.

As cooks began to incorporate fresh produce into many of their dishes, horticulture and botanical gardens became the rage. Scientists and scholarly gentlemen exchanged seeds, translated gardening books and developed hothouses for tender vegetables. They began cultivating mushrooms on beds of putrefying dung. In England, the well-to-do put even such previously distasteful dishes as eggplant on their tables.

DOCTORS NOW SAW FERMENTATION AS THE CENTRAL PROCESS IN DIGESTION. THE COSMOS WAS STILL A KITCHEN, BUT IT WAS NOW EQUIPPED WITH BREWERS' VATS.

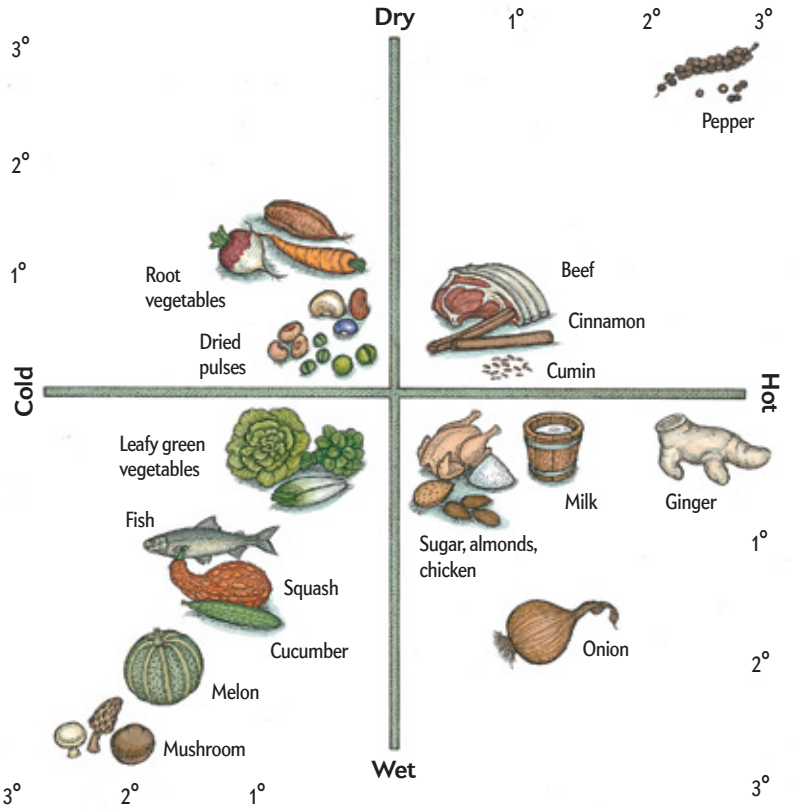
THE FIRST RESTAURANTS

SUBSTANCES rich in oil, such as butter, lard or olive oil, all with the useful sulfurous property of binding the components of salt and mercury, became the basis of a variety of sauces. They were combined with ingredients containing the element

DIETARY DIMENSIONS

16th-Century Classification System

… in which foods were assigned degrees of heat, coldness, wetness and dryness.



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Typical Pre-17th-Century Recipes

Cameline Sauce

"To make an excellent cameline sauce, take skinned almonds and pound and strain them; take raisins, cinnamon, cloves and a little crumb of bread and pound everything together, and moisten with verjuice*; and it is done."
**Sour juice of unripe grapes*

Blancmange

"Take cooked breasts of chicken and put them on a table and shred them into the finest fibers you can. Then wash the rice and dry it, and make it into flour, and put it through a sieve; then moisten this rice flour with goat's, sheep's or almond milk, and boil it in a well-washed and clean pan; and when it begins to boil, add those shredded breasts, with white sugar and fried white pork fat; and keep it away from the smoke, and let it boil gently without excessive fire, so that it becomes as thick as the rice should be. And when you serve it, top it with crushed or pounded sugar, and fried pork fat."

Hypocras

"To make a lot of good hypocras, take an once of cinamonde, known as long tube cinnamon, a knob of ginger, and an equal amount of galangal,* pounded well together, and then take a livre of good sugar; pound this all together and moisten it with a gallon of the best Beaune wine you can get; and let it steep for an hour or two. Then strain it through a cloth bag several times so it will be very clear."
**A root in the ginger family*

The Three Principles

… by which foods were classified in the late 17th century.

The Mercury Principle
Makes food volatile or gaseous, gives it smell (vinegar, wine, meat essence)

The Sulfur Principle
Makes food oily, binds foods high in salt and mercury (oil, butter, lard)

The Salt Principle
Gives food taste (salt, flour)

SOURCE: *THE MEDIEVAL KITCHEN: RECIPES FROM FRANCE AND ITALY*, UNIVERSITY OF CHICAGO PRESS, 1998; HEIDI NOLAND (*recipes*); PATRICIA J. WYNNE (*principles*)

salt—such as flour and table salt—and other ingredients high in mercury—such as vinegar, wine, spirits, and essences of meat or fish. The first recipe for roux, a combination of fat and flour moistened with wine or stock to produce a single delicious taste, appeared in the cookbook *The French Chef,* written in 1651 by François Pierre de la Varenne.

Salads, which combined oil-based dressings and readily digestible greens, also became quite fashionable. Evelyn, for example, promoted vinaigrette salad dressing in his *Acetaria: A Discourse of Sallets,* published in 1699.

As fruits, herbs and vegetables assumed a more prominent place in the main meal, sugar, formerly lauded as a panacea, came in for rough treatment at the hands of the chemical physicians. Some wanted to banish it altogether.

"Under its whiteness," hissed Joseph Duchesne, physician to King Henry IV of France, in 1606, "sugar hides a great blackness"—doctors knew that it blackened the teeth—"and under its sweetness a very great acrimony, such that it equals agua fortis [nitric acid]."

British physician Willis, who had noticed the sugary urine of patients suffering from what doctors later termed diabetes, concurred: "Sugar, distilled by itself, yields a liquor scarcely inferior to aqua fortis…. Therefore it is very probable that mixing sugar with almost all our food, and taken to so great a degree, from its daily use, renders the blood and humours salt and acrid; and consequently scorbutic [tainted by scurvy]."

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The moral was clear: sugar was dangerous, perhaps even a poison. Such dire warnings would surely have given any chef second thoughts about sprinkling it over the main dishes of the meal, leaving the diner no choice but to eat it. Thus, sugar moved to the periphery of the menu, served only in desserts, which were prepared in a separate kitchen. Sugar became the subject of a distinct genre of books dedicated to its decorative, not medical, properties.

Physicians regarded alcoholic spirits and other distilled essences as useful medicines [see "Alcohol in the Western World," on next page]. They and their patients, though, considered a cordial or an eau-de-vie fine for the occasional sip but too strong for everyday use. Less powerful extractions, made from such nutritive foods as meats that had been concentrated by boiling or fermenting, could be more easily digested.

Sometimes the concentrated goodness of a food even showed up as desirable gas bubbles that nourished the brain. Sparkling mineral waters gained immense popularity as spas opened across Europe. At the table, hot and spicy hypocras yielded to cool wines, even to sparkling champagne, which was most likely first produced in the late 17th century.

Chefs made essences of meat or fish from the "musculous Flesh, which is of all [parts of the animal] the most nourishing, that which produces the best juice." They then served this healthy fare in the form of stock, bouillon or jellies made from these liquids. Land animals, they believed, had more nutritious juices than fish or birds did—and of the land animals, beef produced the most restorative extracts.

By 1733 Vincent la Chapelle, a French chef who worked for the earl of Chesterfield in England, had assembled a variety of recipes for delicately garnished beef bouillon in his book *The Modern Cook,* which was quickly translated into French. Before long, entrepreneurs saw an opportunity in this new cuisine, selling "restaurants"—which in French means "restoratives"—to those who could not afford their own chefs.

Eventually Europe's middle classes emulated the aristocracy, developing a taste not only for restaurants but for all the new cuisine. Such foods seemed to offer a certain refinement, not just in the sense of good taste but also in a chemical sense, as the meals represented the most enhanced form of food. As the authors of the gastronomic treatise *The Gifts of Comus,* published in Paris in 1739, put it: "Modern cookery is a kind of chemistry. The cook's science consists today of analyzing, digesting, and extracting the quintessence of foods, drawing out the light and nourishing juices, mingling and blending them together."

SUGAR, FORMERLY LAUDED AS A PANACEA, WAS NOW CONSIDERED DANGEROUS, PERHAPS EVEN A POISON.

This new diet gradually spread across Europe as it simultaneously made its way down the social scale. By the mid- to late 19th century it had become the standard for the English- and French-speaking worlds in Europe, the U.S., Canada and Australia. Other regions, however—the Islamic world and Spanish-speaking parts of the Americas, for example—remained isolated from the chemistry derived from Paracelsus and adopted neither the dietary theory nor the resultant cuisine. (The modern curries of India and moles of Mexico, for instance, resemble the cuisine of pre-Paracelsian northern Europe.)

The Western cuisine born in the 17th century long outlived the dietary theory that inspired it. By the end of the 18th century, chemists and physicians had embarked on the research that was to lead to the modern theories of the role of calories, carbohydrates, proteins, vitamins and minerals in the biochemical processes of digestion. Notably, during the 19th and early 20th centuries, when most of these studies were carried out, nutritionists focused on developing a cheap but adequate diet for factory workers, soldiers and other less affluent people. The shift of emphasis in the medical community from the rich to the poor, though, meant that chefs catering to the well-heeled continued to develop Western cuisine along the lines established in the 17th century.

In the last third of the 20th century, when everyone in the West could afford the cuisine formerly restricted to the wealthy, many became concerned about its dietary foundations. Although they gave fresh fruits and vegetables high marks, they worried about the centrality of fat in sauces such as espagnole, béchamel and more homely gravy. As a result, those sauces have waned in importance, their place taken by other ways of adding flavor such as rubs of herbs and spices and tomato sauce.

Meanwhile sugar has again fallen from favor, derided as little more than "empty" calories. Once more, cooks are shifting to conform to the latest thinking in physiology and nutrition. SA

Rachel Laudan received her doctorate in history and philosophy of science from the University of London. Among her many publications on the history of science is *From Mineralogy to Geology: The Foundations of a Science* (University of Chicago Press 1987). She was co-editor of *The Oxford Companion to the History of Modern Science* (Oxford University Press, 2003). More recently, Laudan has turned to the history of food, winning the Sophie Coe Prize of the Oxford Symposium on Food and Cookery for the essay on which this article is based and the International Association of Culinary Professionals award for *Cuisine and Empire: Cooking in World History* (University of California Press, 2013).

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ADULT BEVERAGES

ALCOHOL IN THE WESTERN WORLD

The role of alcohol in Western civilization has changed dramatically during this millennium. Our current medical interpretation of alcohol as primarily an agent of disease comes after a more complex historical relationship

By Bert L. Vallee

A SUBSTANCE, LIKE A PERSON, MAY HAVE DISTINCT AND EVEN contradictory aspects to its personality. Today ethyl alcohol, the drinkable species of alcohol, is a multifaceted entity; it may be social lubricant, sophisticated dining companion, cardiovascular health benefactor or agent of destruction. Throughout most of Western civilization's history, however, alcohol had a far different role. For most of the past 10 millennia, alcoholic beverages may have been the most popular and common daily drinks, indispensable sources of fluids and calories. In a world of contaminated and dangerous water supplies, alcohol truly earned the title granted it in the Middle Ages: *aqua vitae,* the "water of life."

Western civilization has wine and beer to thank for nourishment and hydration during most of the past 10,000 years. Before the very recent availability of clean, pure water, alcoholic beverages may have been the only safe liquids to drink.

Illustrations by Bryan Chrystie

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Potent evidence opens a window into a societal relationship with alcohol that is simply unimaginable today. Consider this statement, issued in 1777 by Prussia's Frederick the Great, whose economic strategy was threatened by importation of coffee: "It is disgusting to notice the increase in the quantity of coffee used by my subjects, and the amount of money that goes out of the country as a consequence. Everybody is using coffee; this must be prevented. His Majesty was brought up on beer, and so were both his ancestors and officers. Many battles have been fought and won by soldiers nourished on beer, and the King does not believe that coffee-drinking soldiers can be relied upon to endure hardships in case of another war."

Surely a modern leader who urged alcohol consumption over coffee, especially by the military, would have his or her mental competence questioned. But only an eyeblink ago in historical time, a powerful head of government could describe beer in terms that make it sound like mother's milk. And indeed, that nurturing role may be the one alcohol played from the infancy of the West to the advent of safe water supplies for the masses only within the past century.

Natural processes have no doubt produced foodstuffs containing alcohol for millions of years. Yeast, in metabolizing sugar to obtain energy, creates ethyl alcohol as a by-product of its efforts. Occasionally animals accidentally consume alcohol that came into being as fruit "spoiled" in the natural process of fermentation; inebriated birds and mammals have been reported. Humans have a gene for the enzyme alcohol dehydrogenase; the presence of this gene at least forces the conjecture that over evolutionary time animals have encountered alcohol enough to have evolved a way to metabolize it. Ingestion of alcohol, however, was unintentional or haphazard for humans until some 10,000 years ago.

UNTOLD MASSES OF OUR PROGENITORS DIED FROM QUENCHING THEIR THIRST WITH WATER. THE PILGRIMS LANDED AT PLYMOUTH ROCK ONLY BECAUSE THEIR BEER STORES HAD RUN OUT.

About that time, some Late Stone Age gourmand probably tasted the contents of a jar of honey that had been left unattended longer than usual. Natural fermentation had been given the opportunity to occur, and the taster, finding the effects of mild alcohol ingestion provocative, probably replicated the natural experiment. Comrades and students of this first oenologist then codified the method for creating such mead or wines from honey, dates or sap. The technique was fairly simple: leave the sweet substance alone to ferment.

Beer, which relies on large amounts of starchy grain, would wait until the origin and development of agriculture. The fertile river deltas of Egypt and Mesopotamia produced huge crops of wheat and barley; the diets of peasants, laborers and soldiers of these ancient civilizations were cereal-based. It might be viewed as a historical inevitability that fermented grain would be discovered. As in the instance of wine, natural experiments probably produced alcoholic substances that aroused the interest of those who sampled the results. Before the third millennium B.C., Egyptians and Babylonians were drinking beers made from barley and wheat.

Wine, too, would get a boost from agriculture. Most fruit juice, even wild grape juice, is naturally too low in sugar to produce wine, but the selection for sweeter grapes leading to the domestication of particular grape stock eventually led to viniculture. The practice of growing grape strains suitable for wine production has been credited to people living in what is now Armenia, at about 6000 B.C., although such dating is educated guesswork at best.

The creation of agriculture led to food surpluses, which in turn led to ever larger groups of people living in close quarters, in villages or cities. These municipalities faced a problem that still vexes, namely how to provide inhabitants with enough clean, pure water to sustain their constant need for physiological hydration. The solution, until the 19th century, was nonexistent. The water supply of any group of people rapidly became polluted with their waste products and thereby dangerous, even fatal, to drink. How many of our progenitors died attempting to quench their thirst with water can never be known. Based on current worldwide crises of dysentery and infectious disease wrought by unclean water supplies, a safe bet is that a remarkably large portion of our ancestry succumbed to tainted water.

In addition, the lack of liquids safe for human consumption played a part in preventing long-range ocean voyages until relatively recently. Christopher Columbus made his voyage with wine on board, and the Pilgrims landed at Plymouth Rock only because their beer stores had run out. An early order of business was luring brewmasters to the colonies.

ALCOHOL VS. WATER

NEGATIVE EVIDENCE arguing against a widespread use of water for drinking can be found in perusal of the Bible and ancient Greek texts. Both the Old and New Testaments are virtually devoid of references to water as a common human beverage. Likewise, Greek writings make scant reference to water drinking, with the notable exception of positive statements regarding the quality of water from mountain springs. Hippocrates specifically

IN BRIEF

Water was unsafe to drink for most of human history. Evidence from archaeology and ancient literature suggests that for millennia, primitive, low-alcohol beers and wine were the preferred beverages—and common medicines—in regions where people had the genetic ability to metabolize alcohol. All through Western history, the normal state of mind may have been one of inebriation.

Religious authorities endorsed and even produced beer and wine for centuries. But the development of stronger distilled spirits by Islamic Arab alchemists eventually led to growing abuse and health impacts that remain widespread today.

To combat alcohol dependence, some have championed temperance, whereas others have searched for medical cures.

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cited water from springs and deep wells as safe, as was rainwater collected in cisterns. The ancients, through what must have been tragic experience, clearly understood that most of their water supply was unfit for human consumption.

In this context of contaminated water supply, ethyl alcohol may indeed have been mother's milk to a nascent Western civilization. Beer and wine were free of pathogens. And the antiseptic power of alcohol, as well as the natural acidity of wine and beer, killed many pathogens when the alcoholic drinks were diluted with the sullied water supply. Dating from the taming and conscious application of the fermentation process, people of all ages in the West have therefore consumed beer and wine, not water, as their major daily thirst quenchers.

Babylonian clay tablets more than 6,000 years old give beer recipes, complete with illustrations. The Greek *akratidzomai,* which came to mean "to breakfast," literally translates as "to drink undiluted wine." Breakfast apparently could include wine as a bread dip, and "bread and beer" connoted basic necessity much as does today's expression "bread and butter."

The experience in the East differed greatly. For at least the past 2,000 years, the practice of boiling water, usually for tea, has created a potable supply of nonalcoholic beverages. In addition, genetics played an important role in making Asia avoid alcohol: approximately half of all Asian people lack an enzyme necessary for complete alcohol metabolism, making the experience of drinking quite unpleasant. Thus, beer and wine took their place as staples only in Western societies and remained there until the end of the 19th century.

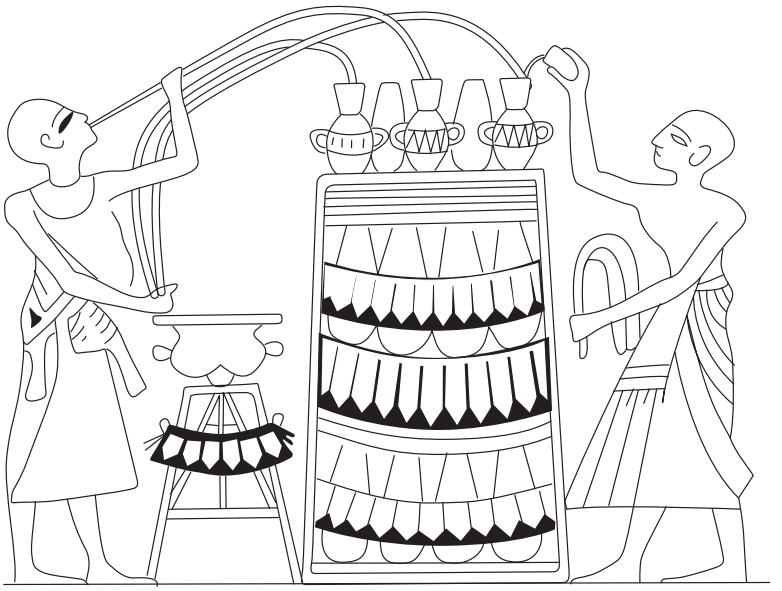
The traditional production of beer and wine by fermentation of cereals and grapes or other fruits produced beverages with low alcohol content compared with those familiar to present-day consumers. The beverages also contained large amounts of acetic acid and other organic acids created during fermentation. Most wines of ancient times probably would turn a modern oenophile's nose; those old-style wines in new bottles would more closely resemble today's vinegar, with some hints of cider, than a prizewinning merlot.

Because the alcohol content of daily staple drinks was low, consumers focused on issues of taste, thirst quenching, hunger satisfaction and storage rather than on intoxication. Nevertheless, the "side effects" of this constant, low-level intake must have been almost universal. Indeed, throughout Western history the normal state of mind may have been one of inebriation.

The caloric value of nonperishable alcoholic beverages may also have had a significant part in meeting the daily energy requirements of societies that might have faced food shortages. In addition, they provided essential micronutrients, such as vitamins and minerals.

Alcohol also served to distract from the fatigue and numbing boredom of daily life in most cultures, while alleviating pain for which remedies were nonexistent. Today people have a plethora of handy choices against common aches and pain. But until the 20th century, the only analgesic generally available in the West was alcohol. From the Book of Proverbs comes this prescription: "Give strong drink unto him that is ready to perish, and wine unto them that be of heavy hearts. Let him drink, and forget his poverty, and remember his misery no more." A Sumerian cuneiform tablet of a pharmacopoeia dated to about 2100 B.C. is generally cited as the oldest preserved record of medicinal alcohol, although Egyptian papyri may have preceded the tablet. Hippocrates' therapeutic system featured wines as remedies for almost all acute or chronic ailments known in his time, and the Alexandrian School of Medicine supported the medical use of alcohol.

ANCIENT WINE



Egyptian paintings show alcohol as integral to the lives of the nobility. This depiction of wines being blended is from Amanemhat's Tomb, circa 1400 B.C.

RELIGION AND MODERATION

THE BEVERAGES of ancient societies may have been far lower in alcohol than their current versions, but people of the time were aware of the potentially deleterious behavioral effects of drinking. The call for temperance began quite early in Hebrew, Greek and Roman cultures and was reiterated throughout history. The Old Testament frequently disapproves of drunkenness, and the prophet Ezra and his successors integrated wine into everyday Hebrew ritual, perhaps partly to moderate undisciplined drinking, thus creating a religiously inspired and controlled form of prohibition.

In the New Testament, Jesus obviously sanctioned alcohol consumption, resorting to miracle in the transformation of water to wine, an act that may acknowledge the goodness of alcohol versus the polluted nature of water. His followers concentrated on extending measures to balance the use and abuse of wine but never supported total prohibition. Saint

SOURCE: *FOOD: THE GIFT OF OSIRIS,* VOL 2, ACADEMIC PRESS, 1977

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Paul and other fathers of early Christianity carried on such moderating attitudes. Rather than castigating wine for its effects on sobriety, they considered it a gift from God, both for its medicinal qualities and for the tranquilizing characteristics that offered relief from pain and the anxiety of daily life.

Traditionally, beer had been the drink of the common folk, whereas wine was reserved for the more affluent. Grape wine, however, became available to the average Roman after a century of vineyard expansion that ended in about 30 B.C., a boom driven by greater profits for wine grapes compared with grain. Ultimately, the increased supply drove prices down, and the common Roman could partake in wine that was virtually free. Roman viniculture declined with the empire and was inherited by the Catholic Church and its monasteries, the only institutions with sufficient resources to maintain production.

For nearly 1,300 years the Church operated the biggest and best vineyards, to considerable profit. Throughout the Middle Ages, grain remained the basic food of peasants and beer their normal beverage, along with mead and homemade wines or ciders. The few critics of alcohol consumption were stymied by the continuing simple fact of the lack of safe alternatives. Hence, despite transitions in political systems, religions and ways of life, the West's use of and opinion toward beer and wine remained remarkably unchanged. But a technological development would alter the relationship between alcohol and humanity.

After perhaps 9,000 years of experience drinking relatively low alcohol mead, beer and wine, the West was faced with alcohol in a highly concentrated form, thanks to distillation. Developed in about A.D. 700 by Arab alchemists (for whom *al kohl* signified any material's basic essence), distillation brought about the first significant change in the mode and magnitude of human alcohol consumption since the beginning of Western civilization. Although yeasts produce alcohol, they can tolerate concentrations of only about 16 percent. Fermented beverages therefore had a natural maximum proof. Distillation circumvents nature's limit by taking advantage of alcohol's 78 degree Celsius (172 degree Fahrenheit) boiling point, compared with 100 degrees C for water. Boiling a water-alcohol mixture puts more of the mix's volatile alcohol than its water in the vapor. Condensing that vapor yields liquid with a much higher alcohol level than that of the starting liquid.

The Arab method—the custom of abstinence had not yet been adopted by Islam—spread to Europe, and distillation of wine to produce spirits commenced on the continent in about A.D. 1100. The venue was the medical school at Salerno, Italy, an important center for the transfer of medical and chemical theory and methods from Asia Minor to the West. Joining the traditional alcoholic drinks of beer and wine, which had low alcohol concentration and positive nutritional benefit, were beverages with sufficient alcohol levels to cause the far-reaching problems still with us today. The era of distilled spirits had begun.

Knowledge of distillation gradually spread from Italy to northern Europe; Alsatian physician Hieronymus Brunschwig described the process in 1500 in *Liber de arte distillandi de compositis,* the first printed book on distillation. By the time Brunschwig was a best-selling author, distilled alcohol had earned its split personality as nourishing food, beneficent medicine and harmful drug. The widespread drinking of spirits followed closely on the heels of the 14th century's bouts with plague, notably the Black Death of 1347–1351. Though completely ineffective as a cure for plague, alcohol did make the victim who drank it at least feel more robust. No other known agent could accomplish even that much. The medieval physician's optimism related to spirits may be attributed to this ability to alleviate pain and enhance mood, effects that must have seemed quite remarkable during a crisis that saw perhaps two thirds of Europe's population culled in a single generation.

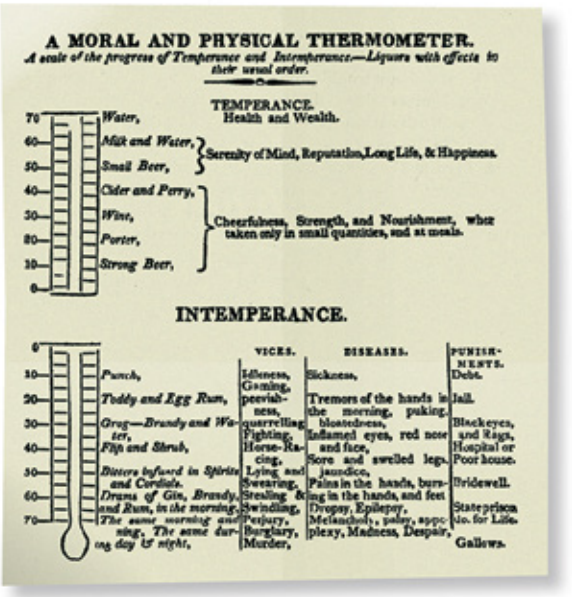
Economic recovery following the subsidence of the plague throughout Europe generated new standards of luxury and increased urbanization. This age witnessed unprecedented ostentation, gluttony, self-indulgence and inebriation. Europe, apparently relieved to have survived the pestilence of the 14th century, went on what might be described as a continentwide bender. Despite the obvious negative effects of drunkenness and despite attempts by authorities to curtail drinking, the practice continued until the beginning of the 17th century, when nonalcoholic beverages made with boiled water became popular. Coffee, tea and cocoa thus began to break alcohol's monopoly on safety.

In the 18th century a growing religious antagonism toward alcohol, fueled largely by Quakers and Methodists and mostly in Great Britain, still lacked real effect or popular support. After all, the Thames River of the time was as dangerous a source of drinking water as the polluted streams of ancient cultures. Dysen-

ANALOGY

Holding One's Temper

Physician and political figure Benjamin Rush used a thermometer metaphor in the early 19th century to illustrate the effects of alcohol. Even after realizing that alcohol abuse was a disease, Rush did allow for the benefits of moderate drinking, seen in the "Temperance" section of his chart.


A MORAL AND PHYSICAL THERMOMETER.
A scale of the progress of Temperance and Intemperance.—Liquors with effects in their usual order.
TEMPERANCE.
Health and Wealth.
Water,
Milk and Water,
Small Beer,
Serenity of Mind, Reputation, Long Life, & Happiness.
Cider and Perry,
Wine,
Porter,
Strong Beer,
Cheerfulness, Strength, and Nourishment, when taken only in small quantities, and at meals.
INTEMPERANCE.
VICES.
DISEASES.
PUNISHMENTS.
Punch,
Toddy and Egg Rum,
Grog—Brandy and Water,
Flip and Shrub,
Bitters infused in Spirits and Cordials.
Drams of Gin, Brandy, and Rum, in the morning.
The same morning and night, The same during day & night,
Idleness, Gaming, peevishness, quarrelling, Fighting, Horse-Racing, Lying and Swearing, Stealing & Swindling, Perjury, Burglary, Murder,
Sickness,
Tremors of the hands in the morning, puking, bloatedness, Inflamed eyes, red nose and face, Sore and swelled legs, jaundice, Pains in the hands, burning in the hands, and feet Dropsy, Epilepsy, Melancholy, palsy, apoplexy, Madness, Despair,
Debt.
Jail.
Blackeyes, and Rags, Hospital or Poor house.
Bridewell.
Statepriscn &c. for Life.
Gallows.

CENTER OF ALCOHOL STUDIES, RUTGERS UNIVERSITY, *QUARTERLY JOURNAL OF STUDIES ON ALCOHOL*, VOL. 4, 1943

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tery, cholera and typhoid, all using filthy water as a vehicle, were major killers and would remain so in the West as recently as the end of the 19th century, rivaling plague in mass destruction.

Only the realization that microorganisms caused disease and the institution of filtered and treated water supplies finally made water a safe beverage in the West. Religious antialcohol sentiment and potable water would combine with one other factor to make it finally possible for a significant percentage of the public to turn away from alcohol. That other factor was the recognition of alcohol dependence as an illness.

DISEASES OF ALCOHOL

THROUGHOUT THE 19TH CENTURY the application of scientific principles to the practice of medicine allowed clinical symptoms to be categorized into diseases that might then be understood on a rational basis. Alcohol abuse was among the earliest medical problems to receive the attention of this approach. Two graduates of the Edinburgh College of Medicine, Thomas Trotter of Britain and Benjamin Rush of the colonies and then the U.S., made the first important contributions to the clinical recognition of alcoholism as a chronic, life-threatening disease. The influence of moralistic antialcohol Methodism may have driven their clinical research, but their findings were nonetheless sound.

In an 1813 essay on drunkenness, Trotter described alcohol abuse as a disease and recognized that habitual and prolonged consumption of hard liquor causes liver disease, accompanied by jaundice, wasting and mental dysfunction, evident even when the patient is sober. Rush published similar ideas in America and to greater effect, given that he was a prominent member of society and a signer of the Declaration of Independence. His personal fame, behind his correct diagnosis of a societal ill, helped to create viewpoints that eventually culminated in the American Prohibition (1919–1933).

Nineteenth-century studies detailed the clinical picture and pathological basis of alcohol abuse, leading to today's appreciation of it as one of the most important health problems facing America and the rest of the world. Alcohol contributes to about 90,000 deaths in this country annually, making it one of the top 10 risk factors for poor health in the U.S. Although the exact number of problem drinkers is difficult to estimate accurately, America is probably home to about 17 million people whose lives are disrupted by their relationship with alcohol.

The overall alcohol problem is far broader. Perhaps 40 percent of Americans have been intimately exposed to the effects of alcohol abuse through a family member. And every year as many as 12,000 children of drinking mothers are robbed of their potential, born with the physical signs and intellectual deficits associated with full-blown fetal alcohol syndrome; thousands more suffer lesser effects. Pharmaceutical treatments for alcoholism remain impractical and inadequate, with total abstinence still the only truly effective approach.

Society and science are at the threshold of new pharmaceutical and behavioral strategies against alcoholism, however. As with any other disease, whether of the individual or the society, a correct diagnosis is crucial to treatment. Alcoholism, in historical terms, has only just been understood and accepted as a disease; we are still coping with the historically recent arrival of concentrated alcohol. The diagnosis having been made and acknowledged, continuing research efforts can be counted on to produce new and more effective treatments based on the growing knowledge of the physiology of alcohol abuse and of addictive substances in general.

Humanity at any moment of history is inevitably caught in that time, as trapped as an insect in amber. The mores, traditions and attitudes of an era inform the individuals then living, often blinding them to the consideration of alternatives. Alcohol today is a substance primarily of relaxation, celebration and, tragically, mass destruction. To consider it as having been a primary agent for the development of an entire culture may be jolting, even offensive to some. Any good physician, however, takes a history before attempting a cure. SA

Bert L. Vallee received his M.D. from New York University in 1943 and joined the faculty of Harvard Medical School in 1945. He was later appointed Edgar M. Bronfman Distinguished Senior Professor and a fellow of the National Academy of Sciences. He established the field of zinc enzymology and performed research on alcohol dehydrogenase, which led to his interest in the history of alcohol. Before his death in 2010, Vallee authored more than 600 scientific publications. He wrote this article in 1998; it was updated for this issue by Rachel Laudan, author of *Cuisine and Empire: Cooking in World History* (University of California Press, 2013).

THE HARD STUFF

Distillation created alcoholic drinks of unprecedented potency. This distillation apparatus appeared in Hieronymus Brunschwig's *Liber de arte distillandi de compositis,* the first book published on the subject, in A.D. 1500. The book featured these claims for distilled alcohol: "It causes a good colour in a person. It heals baldness… kills lice and fleas…. It gives also courage in a person, and causes him to have a good memory."

LIBER DE ARTE DISTILLANDI DE COMPOSITIS, BY HIERONYMUS BRUNSCHWIG, EDITION OF JOHANN GRÜNINGER, 1512 (copy held in Harvard Medical Library collection, Francis A. Countway Library of Medicine)

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INNOVATION

THE AMAZING MULTIMILLION-YEAR HISTORY OF PROCESSED FOOD

It is the dark force, we're told, behind the obesity epidemic, the death of the family farm and Tang. But humans have been "processing" food ever since we learned how to cook, preserve, ferment, freeze, dry or extract. Processed food has powered the evolution of the species, the expansion of empires, the exploration of space. Here are highlights

By Evelyn Kim

As early as 1.8 million years ago

ROASTED MEAT

Fire-kissed food is easier to digest and more nutritious than raw food is. Some anthropologists, such as Richard Wrangham of Harvard University, argue that cooking was the essential step that allowed early humans to develop the big brains characteristic of *Homo sapiens.*

30,000 years ago

BREAD

Agriculture began around 12,000 years ago, but early Europeans were baking bread many thousands of years before that time. In 2010 scientists found surprising evidence of starch grains on crude mortars and pestles at sites in modern-day Italy, Russia and the Czech Republic. The starches came from the roots of cattails and ferns, which early humans pounded into flour, mixed with water and baked into bread.

Bread was portable, dense in nutrients, and spoilage-resistant. It was also a nutritional step backward. Comparative studies show that hunter-gatherers in the Neolithic period ate a more varied and nutritious diet than the farmers of that period did. Hunter-gatherers were also far more efficient in their energy consumption: a farmer had to work for 10 hours to grow food containing as many calories as six hours of foraging typically provided.

Then why bother with bread at all? Anthropologists debate why farming became dominant, but bread and agriculture were clearly codependent. As societies began to rely on bread as a major foodstuff, they were also forced to expend more effort on agriculture (and vice versa).

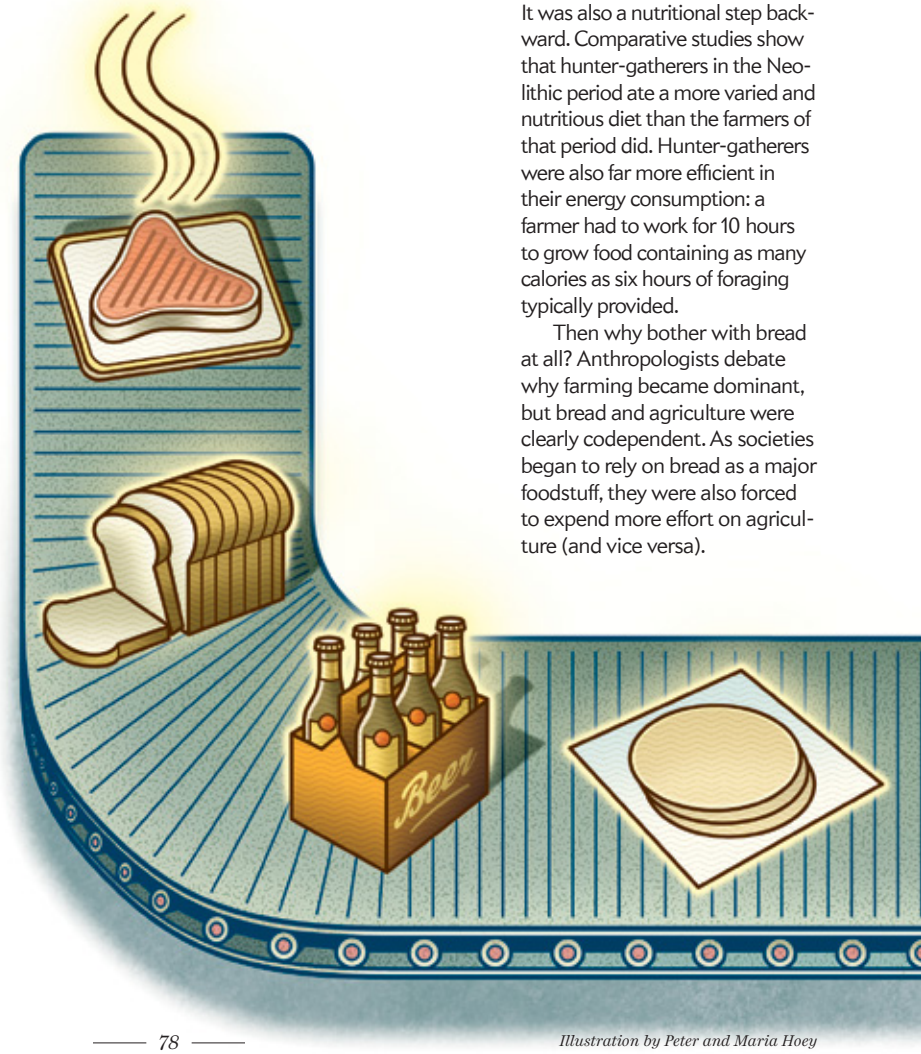

Illustration by Peter and Maria Hoey

MORE TO EXPLORE

The Cambridge World History of Food. Edited by Kenneth F. Kiple and Kriemhild Coneè Ornelas. Cambridge University Press, 2000.

The Oxford Encyclopedia of Food and Drink in America. Second edition. Edited by Andrew F. Smith. Oxford University Press, 2012.

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7000–3000 B.C.
BEER
The birth of beer is hard to place. The oldest physical evidence comes from pottery shards in Iran dated to 3400–3000 B.C., but archaeologists such as Patrick McGovern of the University of Pennsylvania have suggested that the first grog may have been produced as early as 7000 B.C. from rice, grapes, hawthorn berries and honey. Early societies quickly embraced beer: ancient Sumerians may have diverted as much as 40 percent of all grain to brewing.

Modern-day brewers, with help from archaeologists, have attempted to re-create ancient brews. McGovern has partnered with Dogfish Head Craft Brewery to ferment ancient Egyptian and Chinese beverages, whereas Great Lakes Brewing Company, with help from researchers at the University of Chicago, has brewed beer based on a 3,800-year-old ode to the Sumerian beer goddess Ninkasi.

6700 B.C.
TORTILLAS
No written records predate the arrival of Spanish explorers in the Americas, but the earliest archaeological evidence for maize domestication dates back around 8,700 years. Early Americans would soak kernels in a lime solution to create masa, releasing nutrients in the process.

5400 B.C.
WINE
The earliest evidence of wine making has been found in the Zagros Mountains in Iran. Seafaring Phoenicians then spread the practice westward from Lebanon to Egypt and the Mediterranean.

5000 B.C.
CHEESE
Take milk, place it in a stomach removed from a ruminant, and then churn. Scholars suggest this method is probably not too far off from how cheese was invented. The earliest evidence for cheese making comes from 7,000-year-old archaeological sites in Poland, where remains of milk fat were found in perforated ceramic containers that could have served as rudimentary strainers. Yet with the domestication of sheep and goats as early as 8000 B.C. and of cattle a millennium later, it is possible that cheese making has been going on for longer.

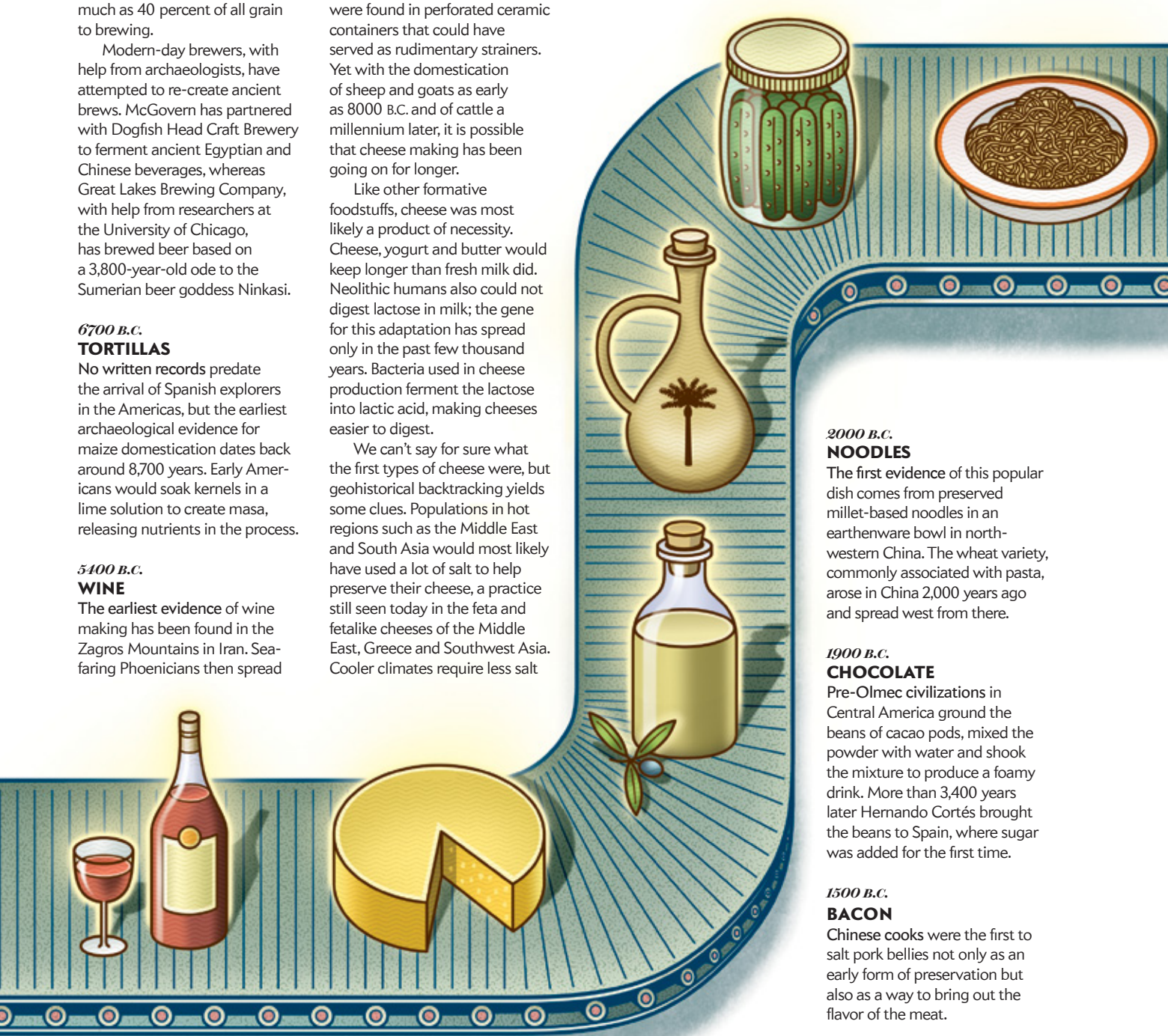
Like other formative foodstuffs, cheese was most likely a product of necessity. Cheese, yogurt and butter would keep longer than fresh milk did. Neolithic humans also could not digest lactose in milk; the gene for this adaptation has spread only in the past few thousand years. Bacteria used in cheese production ferment the lactose into lactic acid, making cheeses easier to digest.

We can't say for sure what the first types of cheese were, but geohistorical backtracking yields some clues. Populations in hot regions such as the Middle East and South Asia would most likely have used a lot of salt to help preserve their cheese, a practice still seen today in the feta and fetalike cheeses of the Middle East, Greece and Southwest Asia. Cooler climates require less salt for preservation, making way for the growth of local microbes that add the characteristic flavors of such famous cheeses as Roquefort, Swiss and Brie.

4500 B.C.
OLIVE OIL
A raw olive is inedible because of its bitterness, but farmers in the eastern Mediterranean have been fermenting olives in lye and then pressing the oil out of them for thousands of years.

3000 B.C.
PALM OIL
Oil made from palm berries—a shelf-stable and cheap staple of modern-day processed food—has been found in ancient Egyptian tombs.

2400 B.C.
PICKLES
Ancient Mesopotamians were the first to pack vegetables in vinegar to preserve them for out-of-season consumption.



2000 B.C.
NOODLES
The first evidence of this popular dish comes from preserved millet-based noodles in an earthenware bowl in northwestern China. The wheat variety, commonly associated with pasta, arose in China 2,000 years ago and spread west from there.

1900 B.C.
CHOCOLATE
Pre-Olmec civilizations in Central America ground the beans of cacao pods, mixed the powder with water and shook the mixture to produce a foamy drink. More than 3,400 years later Hernando Cortés brought the beans to Spain, where sugar was added for the first time.

1500 B.C.
BACON
Chinese cooks were the first to salt pork bellies not only as an early form of preservation but also as a way to bring out the flavor of the meat.

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1000 B.C.

JIANG

Jiang was the precursor of flavorings such as miso and soy sauce that are used across East Asia today. According to the ancient Chinese text *Zhouli* (*Rites of Zhou*), *jiang* was made by mixing meat or fish with salt and *liang qu* (a fermentation starter) and leaving the mixture to mature for 100 days. Like many other fermented foods, its discovery was probably accidental, but *jiang*'s dissemination across East Asia was anything but. The rise of Buddhism across Asia in the first to seventh centuries A.D. most likely brought *jiang* to both Korea and Japan.

500 B.C.

SUGAR

According to Sanskrit texts, cooks in India processed sugarcane into giant crystals by boiling and then cooling extracted sugarcane juice. Nearly a millennium later, Indians invented easy-to-transport granulated sugar, which launched the global sugar trade.

A.D. 400

MUSTARD

One of the first mustard recipes, collected in the Roman cookbook *De re coquinaria,* called for a mixture of ground mustard seed, pepper, caraway, lovage, roasted coriander seeds, dill, celery, thyme, oregano, onion, honey, vinegar, fish sauce and oil.

A.D. 700

KIMCHI

The first kimchi was pretty tame: cabbage fermented with salt. Once the Japanese invaded Korea in the 16th century, taking with them red chilies that Portuguese missionaries had brought to Japan from the New World, Koreans started incorporating fiery elements into the dish.

A.D. 700

SUSHI

Sushi started as a means of fish preservation in Southeast Asia, where salted fish was covered in boiled rice and left to ferment for months. The rotting rice was then scraped off and discarded (because of the waste, sushi has always been a dish for the wealthy) and the soured fish consumed. The process is much like dry-aging beef today—you lose some of the product to rot, but the remainder is more tender and flavorful. By the time of 19th-century Japan, the process of long fermentation was eliminated and the tangy taste replaced by the introduction of vinegar into the rice mixture.

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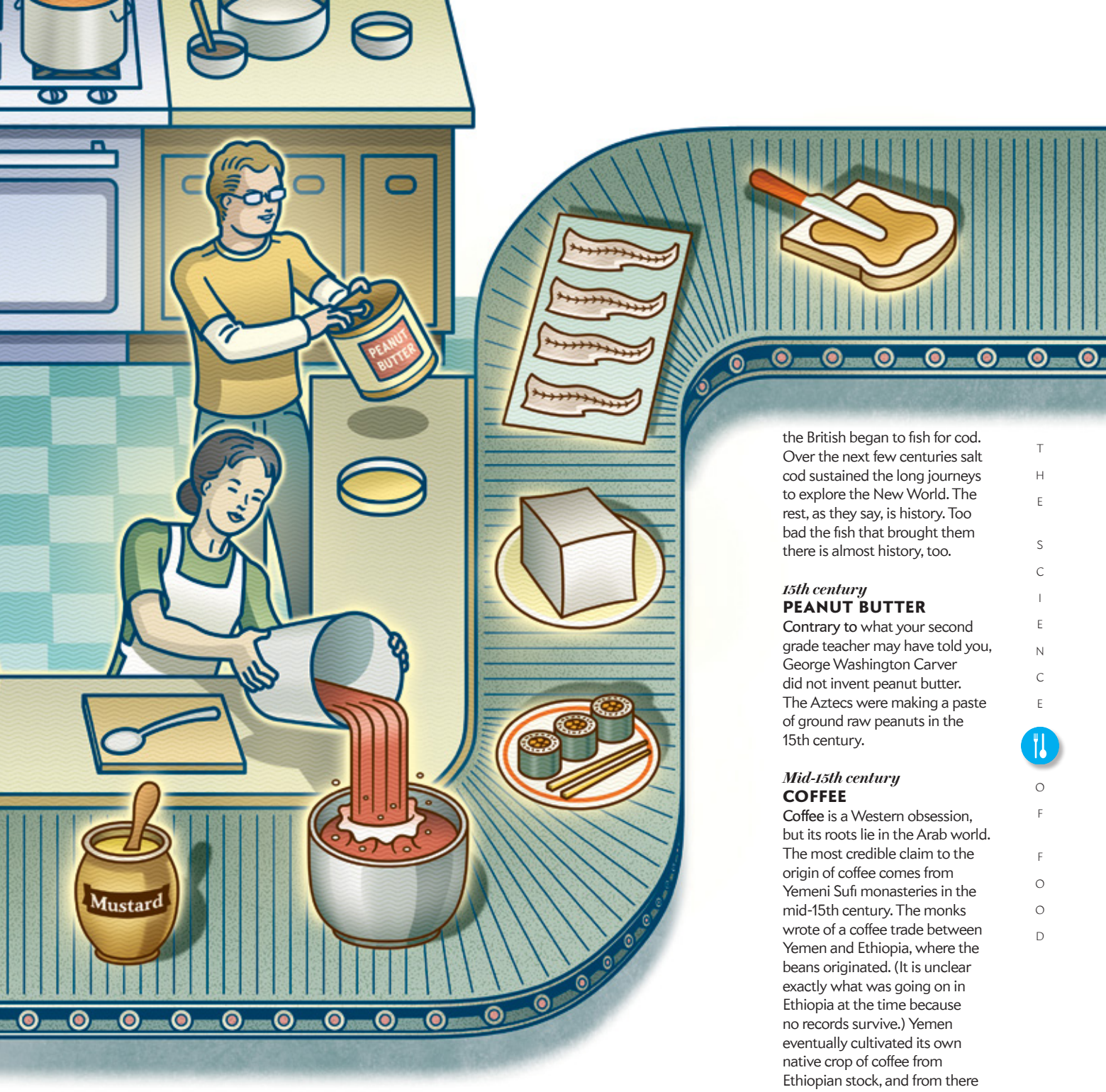

A.D. 965
TOFU

Tofu's origins are mysterious, but the first written record appears in the stories of Chinese writer Tao Ku. He writes of a vice mayor who was so poor, he was forced to buy tofu—a coagulated gel made from cooked soybeans—instead of mutton.

10th century
SALT COD

Although dried cod had been feeding the Vikings since the ninth century, salt changed it from a local foodstuff to a global phenomenon. Salt allowed for cod to be readily dried and preserved even in wet, humid or warm environments, such as a fishing boat. The change began when Basque sailors met Viking fishers and their vast supplies of cod near the Faeroe Islands during the 10th century. By figuring out how to preserve the fish onboard, the Basques found their piscine cash cow. Catholic edict at the time dictated a meatless meal on Friday, which drove salt cod's popularity. Soon the Portuguese, the French and the British began to fish for cod. Over the next few centuries salt cod sustained the long journeys to explore the New World. The rest, as they say, is history. Too bad the fish that brought them there is almost history, too.

15th century
PEANUT BUTTER

Contrary to what your second grade teacher may have told you, George Washington Carver did not invent peanut butter. The Aztecs were making a paste of ground raw peanuts in the 15th century.

Mid-15th century
COFFEE

Coffee is a Western obsession, but its roots lie in the Arab world. The most credible claim to the origin of coffee comes from Yemeni Sufi monasteries in the mid-15th century. The monks wrote of a coffee trade between Yemen and Ethiopia, where the beans originated. (It is unclear exactly what was going on in Ethiopia at the time because no records survive.) Yemen eventually cultivated its own native crop of coffee from Ethiopian stock, and from there it spread to Egypt, Damascus and Mecca. By the 16th century coffeehouses, or *kaveh kanes,* had spread across the Arabian Peninsula.

Coffee was first administered for stomachaches, torpor, narcolepsy and other ailments. Yet coffee was not merely curative; several Arabic writers noted its powers of sociability. Perhaps too much so: the culture of coffee and coffeehouses, with their gossip and game playing,

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prompted the governor of Mecca to declare a ban on the drink in 1511. After a 13-year caffeine headache, the Turkish Sultan Selim I overturned the ban.

For European travelers and explorers of the 16th century, coffee was another curiosity of the Orient. In one of the earliest allusions to coffee by a European, in 1582 German physician and botanist Leonhard Rauwolf described a "good drink which [Turks and Arabs] greatly esteem.... It is nearly as black as ink and helpful against stomach complaints." In a move of early modern marketing, Venetian merchants started importing coffee from the Middle East in the late 16th century as a luxury drink. By the mid-17th century the French, the British and the Dutch all had the buzz.

1767
CARBONATED WATER
Joseph Priestly, the British natural philosopher who discovered oxygen, invented carbonated water after placing a bowl of water above a brewery in Leeds, England.

1894
CORN FLAKES
To satisfy the vegetarian diets advocated by Seventh-Day Adventists, John Harvey Kellogg and his younger brother, Will Keith Kellogg, developed corn flakes in 1894 as part of a diet regimen at his Battle Creek, Mich., sanitarium.

1908
MSG
German agricultural chemist Karl Ritthausen originally discovered glutamic acid, of which monosodium glutamate (MSG) is just one variation, in 1866. Much like his contemporaries in Germany, Ritthausen was part of a growing field, started by a founder of organic chemistry (and inventor of nitrogen-based fertilizers), Justus von Liebig, to look at the chemical basis for naturally occurring substances.

About 40 years later a Japanese chemist, Kikunae Ikeda, who trained as an organic chemist in Germany, tried to replicate the success of his German colleagues, especially that of von Liebig, who became wealthy from creating dehydrated beef stock. Ikeda, like Liebig, wanted to find a way to do the same for Japanese cuisine—that is, create a means of chemically reproducing the flavor of kombu dashi, a staple seaweed-based stock. In 1908, after evaporating a large quantity of dashi broth, he found a residue, tasted it and realized it was the essence of Japanese flavor. Publishing his results in the *Journal of the Chemical Society of Tokyo* in 1909, Ikeda declared that his study had found that seaweed contains glutamates and that glutamates create the familiar yet theretofore undesignated taste umami.

1926
SPAM
The first iteration of what became Spam was called "Hormel spiced ham," and it was just cured pork shoulder in a can. Competitors quickly launched their own versions. To differentiate his product, Jay Hormel changed the recipe in 1937, grinding up the pork, adding salt and spices, and encasing the meat in an aspic gelatin. Most important, Hormel rebranded the product with the catchy name "Spam"—short for "shoulder of pork and ham"—before World War II broke out. The U.S. Army, deciding that Spam was the perfect tent food, bought 150 million pounds of it over the course of the war to feed Allied troops all over the world. In the postwar years, wherever U.S. troops went, cans of Spam followed.

During the Korean War, it became unofficial currency; surplus cans flooded the black market and were used to pay for doctors' visits and military intelligence. To this day, Spam remains a popular product across Korea and the rest of Asia, with Spam added to traditional foods such as *kimbap* and *chanpuru.*

1950s
CHICKEN NUGGETS
Robert C. Baker, a food scientist at Cornell University, ground up chicken parts and coated them with breading as a way to increase demand for chickens in upstate New York.

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1957
HIGH-FRUCTOSE CORN SYRUP

The search for sugar substitutes began as early as 1806, when Napoleon Bonaparte offered a huge reward to anyone who could find a chemical workaround to the British blockade of the French Caribbean sugar plantations. A century and a half later American scientists discovered a way to use enzymes to convert glucose in cornstarch to fructose; in 1967 Japanese scientist Yoshiyuki Takasaki created a cost-effective industrial process. Food companies loved the low cost and the ease with which liquid corn syrup could be dissolved into sodas.

1959
TANG

Scientists at General Foods worked for years to create a powdered orange juice substitute, but their concoctions had unpleasantly bitter tastes. They succeeded by abandoning their ambitions to include all of O.J.'s vitamins and minerals.

1996
PLUMPY'NUT

This nutrient-dense, vitamin-fortified food product made from peanuts, vegetable oil, powdered milk and sugar was designed to help severely malnourished children gain weight.

2013
LAB-GROWN MEAT

The first public taste test of in vitro meat took place in London and featured a burger grown from bovine stem cells.

Evelyn Kim is a writer and educator living in Copenhagen. Her work examines the intersection of the history of science, food and the environment.

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SUSTAINABILITY

CAN WE FEED THE WORLD AND SUSTAIN THE PLANET?

A five-step global plan could double food production by 2050 while greatly reducing environmental damage

By Jonathan A. Foley

RIGHT NOW ABOUT ONE BILLION PEOPLE SUFFER FROM CHRONIC HUNGER. THE WORLD'S farmers grow enough food to feed them, but it is not properly distributed and, even if it were, many cannot afford it, because prices are escalating. But another challenge looms. By 2050 the world's population will increase by two billion or three billion, which will likely double the demand for food, according to several studies. Demand will also rise because many more people will have higher incomes, which means they will eat more, especially meat. Increasing use of cropland for biofuels will put additional demands on our farms. So even if we solve today's problems of poverty and access—a daunting task—we will also have to produce twice as much to guarantee adequate supply worldwide. And that's not all.

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By clearing tropical forests, farming marginal lands, and intensifying industrial farming in sensitive landscapes and watersheds, humankind has made agriculture the planet's dominant environmental threat. Agriculture already consumes a large percentage of the earth's land surface and is destroying habitat, using up freshwater, polluting rivers and oceans, and emitting greenhouse gases more extensively than almost any other human activity. To guarantee the globe's long-term health, we must dramatically reduce agriculture's adverse impacts.

The world's food system faces three incredible, interwoven challenges. It must guarantee that all seven billion people alive today are adequately fed; it must double food production in the next 40 years; and it must become truly environmentally sustainable—all at the same time.

Could these simultaneous goals possibly be met? An international team of experts, which I coordinated, has settled on five steps that, if pursued together, could increase by more than 100 percent the food available for human consumption globally while substantially reducing greenhouse gas emissions, biodiversity losses, water use and water pollution. Tackling the triple challenge will be one of the most important tests humanity has ever faced. It is fair to say that our response will determine the fate of our civilization.

BUMPING UP AGAINST BARRIERS

AT FIRST BLUSH, the way to feed more people seems clear: grow more food, by expanding farmland and improving yield (crops harvested per hectare). Unfortunately, the world is running into significant barriers on both counts.

Society already uses about 37 percent of the earth's land surface, not counting Greenland or Antarctica, for farms or pastures. Agriculture is by far the biggest human use of land on the planet; nothing else comes close. And most of that 37 percent covers the *best* farmland. Much of the remainder is covered by deserts, mountains, tundra, ice, cities, parks and other unsuitable growing areas. The few remaining frontiers are mainly in tropical forests and savannas, which are vital to the stability of the globe, especially as stores of carbon and biodiversity. Expanding into those areas is not a good idea, yet five million to 10 million hectares of cropland have been created in each of the past 20 years, with a significant portion of that land conversion happening in the tropics. These additions enlarged the net area of cultivated land by only 3 percent, however, because of farmland losses caused by urban development and other forces, particularly in temperate zones.

Improving yield also sounds enticing.

TO GUARANTEE THE GLOBE'S LONG-TERM HEALTH, WE MUST DRAMATICALLY REDUCE AGRICULTURE'S ADVERSE IMPACTS.

Yet our research team found that average global crop yield increased by just 20 percent from 1985 to 2005—far less than had been reported. Cereals yield has been rising at less than 2 percent a year since 2000 and yields of pulses (beans, lentils) and root crops by less than 1 percent—rates that are nowhere near enough to double food production by midcentury.

Feeding more people would be easier if all the food we grew went into human hands. But only 60 percent of the world's crops are meant for people: mostly grains, followed by pulses, oil plants, vegetables and fruits. Another 35 percent is used for animal feed, and the final 5 percent goes to biofuels and other industrial products. Meat is the biggest issue here. Even with the most efficient meat and dairy systems, feeding crops to animals reduces the world's potential food supply. Grain-fed cattle operations typically use at least 100 kilograms of grain to make one kilogram of edible, boneless beef protein [see "The Greenhouse Hamburger," on page 108]. Chicken and pork are more efficient, and grass-fed beef converts nonfood material into protein. Overall, grain-fed meat production systems are a drain on the global food supply.

Another deterrent to growing more food is damage to the environment, which is already extensive. Only our use of energy, with its profound impacts on climate and ocean acidification, rivals the sheer magnitude of agriculture's environmental footprint. Our research team has estimated that by 2010 agriculture had already cleared or radically transformed 70 percent of the world's prehistoric grasslands, 50 percent of the savannas, 45 percent of the temperate deciduous forests and 25 percent of the tropical forests. Since the last ice age, nothing has disrupted ecosystems more. Agriculture's physical footprint is nearly 60 times that of the world's pavements and buildings.

Freshwater is another casualty. Humans use an astounding 4,000 cubic kilometers of water per year, mostly withdrawn from rivers and aquifers. Irrigation accounts for 70 percent of the draw. If we count only consumptive water use—water that is used and not returned to the watershed—irrigation climbs to 80 or 90 percent of the total. As a result, many large rivers, such as the Colorado, have diminished flows, some have dried up altogether, and many places have rapidly declining water tables, including regions of the U.S. and India.

Water is not only disappearing, it is being contaminated. Fertilizers, herbicides and pesticides are being spread at incredible levels and are found in nearly every ecosystem. The flows of phosphorus and nitrogen through the environment have more than doubled since 1960, causing widespread water pollution and enor-

IN BRIEF

The world must solve three food problems simultaneously: end hunger, double food production by 2050, and do both while drastically reducing agriculture's damage to the environment.

Five solutions, pursued together, can achieve these goals: stop agriculture from consuming more tropical land, boost the productivity of farms that have the lowest yields, raise the efficiency of water and fertilizer use worldwide, reduce per capita meat consumption, and reduce waste in food production and distribution.

A system for certifying foods based on how well each one delivers nutrition and food security and limits environmental and social costs would help the public choose products that push agriculture in a more sustainable direction.

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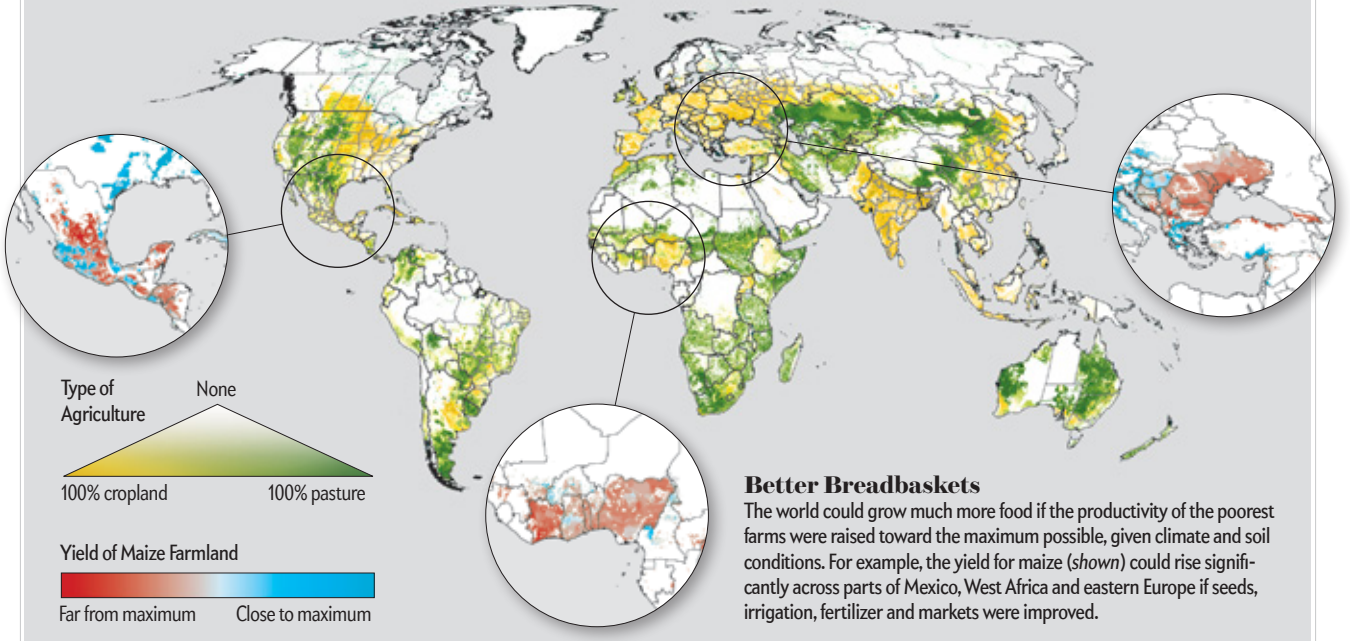
Farming Hits the Wall, but Not the Ceiling

Humankind now farms 37 percent of the earth's ice-free land. Crops take up roughly one third of that area; pastures and rangelands for livestock cover the rest. Little room exists for expansion because deserts, mountains, tundra or cities cover most of the remaining land. Still, farms in many existing areas (*insets*) could be more productive.



Better Breadbaskets
The world could grow much more food if the productivity of the poorest farms were raised toward the maximum possible, given climate and soil conditions. For example, the yield for maize (*shown*) could rise significantly across parts of Mexico, West Africa and eastern Europe if seeds, irrigation, fertilizer and markets were improved.

COURTESY OF JAMES GERBER *Institute on the Environment, University of Minnesota (maps)*

mous hypoxic "dead zones" at the mouths of many of the world's major rivers. Ironically, fertilizer runoff from farmland—in the name of growing more food—compromises another crucial source of nutrition: coastal fishing grounds. Fertilizer certainly has been a key ingredient of the green revolution that has helped feed the world, but when nearly half the fertilizer we apply runs off rather than nourishes crops, we clearly can do better.

Farming also accounts for 10 to 12 percent of the warming effects of greenhouse gases released by human activity—a contribution equal to that of all the road vehicles on the planet. Most of the direct emissions from farming come from methane produced by animals and rice paddies and from nitrous oxide released by overfertilized soils. Add in the effects of tropical deforestation and other land clearing, and agriculture's share of global emissions rises to 24 percent of the total.

FIVE SOLUTIONS

MODERN AGRICULTURE has been an incredibly positive force in the world, but we can no longer ignore its dwindling ability to expand or the mounting environmental harm it imposes. Previous approaches to solving food issues were often at odds with environmental imperatives. We could boost food production by clearing more land or using more water and chemicals but only at a cost to forests, streams and wetlands. Or we could restore ecosystems by taking farmland out of cultivation but only by reducing food production. This either-or approach is no longer acceptable. We need truly integrated solutions.

After months of research and deliberation—based on analysis of newly generated global agricultural and environmental data—our international team settled on a five-point plan that deals with food and environmental challenges together.

Stop expanding agriculture's footprint. Our first recommendation is to slow and ultimately stop the expansion of agriculture, particularly into tropical forests and savannas. The demise of these ecosystems has far-reaching impacts on the environment, especially through lost biodiversity and increased carbon dioxide emissions (from clearing land).

Slowing deforestation would dramatically reduce environmental damage while imposing only minor constraints on global food production. The resulting dip in farm capacity could be offset by reducing the displacement of more productive croplands by urbanization, degradation and abandonment.

Many proposals have been made to reduce deforestation. One of the most promising has been the Reducing Emissions from Deforestation and Degradation (REDD) mechanism. Under REDD, rich nations pay tropical nations to protect their rain forests, in exchange for carbon credits. Other mechanisms include developing certification standards for agricultural products so that supply chains can be assured that crops were not grown on lands created by deforestation. Also, better biofuel policy—one that relies on nonfood crops such as switchgrass instead of food crops—could make vital farmland newly available.

Close the world's yield gaps. To double global food production without expanding agriculture's footprint, we must signifi-

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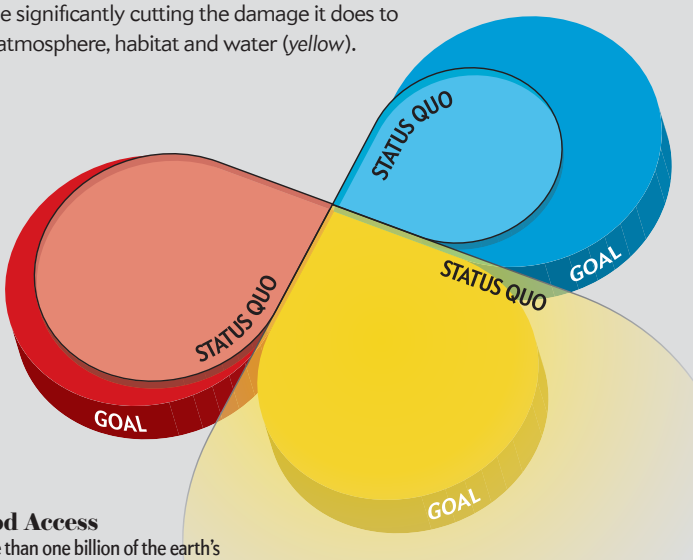
Output Expands, Harm Contracts

To feed the world without harming the planet, agriculture will have to produce much more food (*blue*) and find better ways to distribute it (*red*), while significantly cutting the damage it does to the atmosphere, habitat and water (*yellow*).



Food Production
By 2050 global population will be two billion to three billion greater, and a larger proportion of people will have higher incomes, so they will consume more per person. Farmers will need to grow twice as much as they do today.

Food Access
More than one billion of the earth's seven billion people suffer from chronic hunger. Poverty and poor distribution of food must be overcome to provide adequate calories for everyone.

Environmental Damage
To reduce harm, agriculture must stop expanding into tropical forests, raise the productivity of underperforming farmland (which could boost production 50 to 60 percent), use water and fertilizer far more efficiently, and prevent soil degradation.

cantly improve yields of existing farmlands. Two options exist. We can boost the productivity of our best farms—raising their "yield ceiling" through improved crop genetics and management. Or we can improve the yields of the world's least productive farms—closing the "yield gap" between a farm's current yield and its higher potential yield. The second option provides the largest and most immediate gain, especially in regions where hunger is most acute.

Our research group analyzed global patterns of crop yields and found significant yield gaps in many regions: most notably parts of Africa, Central America and eastern Europe. In these regions, better seeds, more effective fertilizer application and more efficient irrigation could produce much more food without increasing the amount of land under cultivation. Our analysis suggests that closing the yield gap for the world's top 16 crops could increase total food production by 50 to 60 percent, without causing much additional environmental damage.

Reducing yield gaps in the least productive agricultural lands may often require the use of additional chemicals and water. Farmers will have to irrigate and fertilize in responsible ways. They can also make use of other yield-lifting techniques, such as reduced tillage, which disturbs less soil and thus minimizes erosion. Cover crops planted between food-crop seasons suppress weeds and add nutrients and nitrogen to the soil when plowed under. Lessons from organic and agroecological systems can also be adopted, such as leaving crop residues on fields so that they decompose into nutrients. To close the world's yield gaps, we also have to overcome serious economic and social challenges, including better distribution of fertilizer and seed varieties to farms in impoverished regions and improved access to global markets for many regions.

Use resources much more efficiently. To reduce the environmental impacts of agriculture, low- and high-yield regions alike must practice agriculture in ways that produce vastly greater output of crops per unit input of water, fertilizer and energy.

On average, it takes about one liter of irrigation water to grow one calorie of food. Some places use much more, however. Our analysis found that farms can significantly curb water use without much reduction in food production, especially in dry climates. Primary strategies include drip irrigation (where water is applied directly to the plant's base and not wastefully sprayed into the air); mulching (covering the soil with organic matter to retain moisture); and reducing water lost from irrigation systems (by lessening evaporation from canals and reservoirs).

With fertilizers, we face a kind of Goldilocks problem. Some places have too few nutrients and therefore poor crop production, whereas others have too much, leading to pollution. Almost no one uses fertilizers "just right." Amazingly, only 10 percent of the world's cropland generates 30 to 40 percent of agriculture's fertilizer pollution. Our analysis identified hotspots on the planet—particularly in the central U.S., China, northern India and western Europe—where farmers could substantially reduce fertilizer use with little or no impact on food production.

Among the actions that can fix wasteful overfertilization are policy and economic incentives, such as payments to farmers for: promoting watershed stewardship and protection, reducing excessive fertilizer use, improving manure management (especially manure storage, so that less runs off into the watershed during a storm), capturing excess nutrients through recycling, and instituting other conservation practices. In addition, wetlands could be restored to enhance their capacity to act as natural sponges that filter out nutrients in runoff.

Here again, reduced tillage can help nourish the soil, as can precision agriculture (applying fertilizer and water only when and where they are needed and most effective) and organic farming techniques.

Graphic by Jen Christiansen

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Shift diets away from meat. We can dramatically increase global food availability and environmental sustainability by using more of our crops to feed people directly and less to fatten livestock.

Globally, humans could net up to three quadrillion additional calories every year—a 50 percent increase from our current supply—by switching to all-plant diets. Naturally, our current diets and uses of crops have many economic and social benefits, and our preferences are unlikely to change completely. Still, even small shifts in diet, say, from grain-fed beef to poultry, pork or pasture-fed beef, can pay off handsomely.

Reduce food waste. A final, obvious but often neglected recommendation is to reduce waste in the food system. Roughly 30 percent of the food produced on the planet is discarded, lost, spoiled or consumed by pests.

In rich countries, much of the waste takes place at the consumer end of the system, in restaurants and trash cans. Simple changes in our daily consumption patterns—reducing oversize portions, the food thrown in the garbage, and the number of takeout and restaurant meals—could significantly trim losses, as well as our expanding waistlines. In poorer countries, the losses are similar in size but occur at the producer end, in the form of failed crops, stockpiles ruined by pests or spoilage, or food that is never delivered because of bad infrastructure and markets. Improved storage, refrigeration and distribution systems can cut waste appreciably. Moreover, better market tools can connect people who have crops to those who need them, such as cell-phone systems in Africa that link suppliers, traders and purchasers.

Although completely eliminating waste from farm to fork is not realistic, even small steps would be extremely beneficial. Targeted efforts—especially reducing waste of the most resource-intensive foods such as meat and dairy—could make a big difference.

MOVING TOWARD A NETWORKED FOOD SYSTEM

IN PRINCIPLE, our five-point strategy can address many food security and environmental challenges. If they were done together, the steps could increase the world's food availability by 100 to 180 percent while significantly lowering greenhouse gas emissions, biodiversity losses, water use and water pollution.

FEEDING NINE BILLION PEOPLE IN A TRULY SUSTAINABLE WAY WILL BE ONE OF THE GREATEST CHALLENGES OUR CIVILIZATION HAS HAD TO CONFRONT.

It is important to emphasize that all five points (and perhaps more) must be pursued simultaneously. No single strategy is sufficient to solve all our problems. Think silver buckshot, not a silver bullet. We have tremendous successes from the green revolution and industrial-scale agriculture to build on, along with innovations in organic farming and local food systems. Let's take the best ideas and incorporate them into a new approach—a sustainable food system that focuses on nutritional, social and environmental performance, to bring responsible food production to scale.

We can configure this next-generation system as a network of local agricultural systems that are sensitive to nearby climate, water resources, ecosystems and culture and that are connected through efficient means of global trade and transport. Such a system could be resilient and pay farmers a living wage.

One device that would help foster this new food system would be the equivalent of the Leadership in Energy and Environmental Design program now in place for constructing new commercial buildings sustainably. This LEED program awards increasingly higher levels of certification based on points that are accumulated by incorporating any of a wide range of green options, from solar power and efficient lighting to recycled building materials and low construction waste.

For sustainable agriculture, foods would be awarded points based on how well they deliver nutrition, food security and other public benefits, minus their environmental and social costs. This certification would help us get beyond current food labels such as "local" and "organic," which really do not tell us much about what we are eating. Instead we can look at the whole performance of our food—across nutritional, social and environmental dimensions—and weigh the costs and benefits of different farming approaches.

Imagine the possibilities: sustainable citrus and coffee from the tropics, connected to sustainable cereals from the temperate zone, supplemented by locally grown greens and root vegetables, all grown under transparent, performance-based standards. Use your smartphone and the latest sustainable food app, and you will learn where your food came from, who grew it, how it was grown, and how it ranks against various social, nutritional and environmental criteria. And when you find food that works, you can tweet about it to your social network of farmers and foodies.

The principles and practices of our different agricultural systems—from large-scale commercial to local and organic—provide the foundation for grappling with the world's food security and environmental needs. Feeding nine billion people in a truly sustainable way will be one of the greatest challenges our civilization has had to confront. It will require the imagination, determination and hard work of countless people from all over the world. There is no time to lose. SA

Jonathan A. Foley is executive director of the California Academy of Sciences in San Francisco. From 2008 to 2014, he led the Institute on the Environment at the University of Minnesota.

MORE TO EXPLORE

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BIOTECHNOLOGY

ARE ENGINEERED FOODS EVIL?

Proponents of genetically modified crops say the technology is the only way to feed a warming, increasingly populous world. Critics say we tamper with nature at our peril. Who is right?

By David H. Freedman

ROBERT GOLDBERG SAGS INTO HIS DESK CHAIR AND GESTURES AT THE AIR. "FRANKENSTEIN monsters, things crawling out of the lab," he says. "This the most depressing thing I've ever dealt with."

Goldberg, a plant molecular biologist at the University of California, Los Angeles, is not battling psychosis. He is expressing despair at the relentless need to confront what he sees as bogus fears over the health risks of genetically modified (GM) crops. Particularly frustrating to him, he says, is that this debate should have ended decades ago, when researchers produced a stream of exonerating evidence: "Today we're facing the same objections we faced 40 years ago."

Across campus, David Williams, a cellular biologist who specializes in vision, has the opposite complaint. "A lot of naive science has been involved in pushing this technology," he says. "Thirty years ago we didn't know that when you throw any gene into a different genome, the genome reacts to it. But now anyone in this field knows the genome is not a static environment. Inserted genes can be transformed by several different means, and it can happen generations later." The result, he insists, could very well be potentially toxic plants slipping through testing.

Williams concedes that he is among a tiny minority of biologists raising sharp questions about the safety of GM crops. But he believes this is only because the field of plant molecular biology is protecting its interests. Funding, much of it from the companies that sell GM seeds, heavily favors researchers who are exploring ways to further the use of genetic modification in agriculture. He says that biologists who point out health or other risks associated with GM crops—who merely report or defend experimental findings that imply there may be risks—find themselves the focus of vicious attacks on their credibility, which leads scientists who see problems with GM foods to keep quiet.

Whether Williams is right or wrong, one thing is undeniable: despite overwhelming evidence that GM crops are safe to eat, the debate over their use continues to rage, and in some parts of the world, it is growing ever louder. Skeptics would argue that this contentiousness is a good thing—that we cannot be too cautious when tinkering with the genetic basis of the world's food supply. To researchers such as Goldberg, however, the persistence of fears about GM foods is nothing short of exasperating. "In spite of hundreds of millions of genetic experiments involving every type of organism on earth," he says, "and people eating billions of meals without a problem, we've gone back to being ignorant."

So who is right: advocates of GM or

KEVIN VAN AELST

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critics? When we look carefully at the evidence for both sides and weigh the risks and benefits, we find a surprisingly clear path out of this dilemma.

BENEFITS AND WORRIES

THE BULK OF THE SCIENCE on GM safety points in one direction. Take it from David Zilberman, a U.C. Berkeley agricultural and environmental economist and one of the few researchers considered credible by both agricultural chemical companies and their critics. He argues that the benefits of GM crops greatly outweigh the health risks, which so far remain theoretical. The use of GM crops "has lowered the price of food," Zilberman says. "It has increased farmer safety by allowing them to use less pesticide. It has raised the output of corn, cotton and soy by 20 to 30 percent, allowing some people to survive who would not have without it. If it were more widely adopted around the world, the price [of food] would go lower, and fewer people would die of hunger."

In the future, Zilberman says, those advantages will become all the more significant. The United Nations Food and Agriculture Organization estimates that the world will have to grow 70 percent more food by 2050 just to keep up with population growth. Climate change will make much of the world's arable land more difficult to farm. GM crops, Zilberman asserts, could produce higher yields, grow in dry and salty land, withstand high and low temperatures, and tolerate insects, disease and herbicides.

Despite such promise, much of the world has been busy banning, restricting and otherwise shunning GM foods. Nearly all the corn and soybeans grown in the U.S. are genetically modified, but only one GM crop, Monsanto's MON810 maize, is accepted in the European Union. Nine E.U. nations prohibit cultivating GM crops. Throughout Asia, including in India and China, governments have yet to approve most GM crops, including an insect-resistant rice that produces higher yields with less pesticide. In Africa, where millions go hungry, several nations have refused to import GM foods in spite of their lower costs (the result of higher yields and a reduced need for water and pesticides). Kenya has banned them altogether amid widespread malnutrition. Only two countries, Bangladesh and the Philippines, have plans to grow Golden Rice, a crop engineered to deliver more vitamin A than spinach does (rice normally contains no vitamin A), even though vitamin A deficiency causes more than one million deaths and half a million cases of irreversible blindness annually in low-income countries.

Globally, only a tenth of the world's cropland includes GM plants. Five countries—the U.S., Canada, Brazil, India and Argentina—grow 90 percent of the planet's GM crops. Other Latin American countries have been pushing away from the plants. And even in the U.S., voices decrying genetically modified foods are becoming louder. More than 30 states have already considered GM-labeling or other anti-GM bills, and six have passed them.

The fear fueling all this activity has a long history. The public has been worried about the safety of GM foods since scientists at the University of Washington developed the first genetically modified tobacco plants in the 1970s. In the mid-1990s, when the first GM crops reached the market, Greenpeace, the Sierra Club, Ralph Nader, Prince Charles and a number of celebrity chefs took highly visible stands against them. Consumers in Europe became particularly alarmed: a survey conducted in 1997, for example, found that 69 percent of the Austrian public saw serious risks in GM foods, compared with only 14 percent of Americans.

In Europe, skepticism about GM foods has long been bundled with other concerns, such as a resentment of American agribusiness. Whatever it is based on, however, the European attitude reverberates across the world, influencing policy in countries where GM crops could have tremendous benefits. "In Africa, they don't care what us savages in America are doing," Zilberman says. "They look to Europe and see countries there rejecting GM, so they don't use it." Forces fighting genetic modification in Europe have rallied support for "the precautionary principle," which holds that given the kind of catastrophe that would emerge from loosing a toxic, invasive GM crop on the world, GM efforts should be shut down until the technology is proved absolutely safe.

But as medical researchers know, nothing can really be "proved safe." One can only fail to turn up significant risk after trying hard to find it—as is the case with GM crops.

A CLEAN RECORD

THE HUMAN RACE has been selectively breeding crops, thus altering plants' genomes, for millennia. Ordinary wheat has long been strictly a product of human bioengineering; it could not exist outside of farms, because its seeds do not scatter. For some 60 years scientists have been using "mutagenic" techniques to scramble the DNA of plants with radiation and chemicals, creating mutant strains of wheat, rice, peanuts and pears that have since become agricultural mainstays. The practice has inspired little objection from scientists or the public and has caused no known health problems.

The difference is that selective breeding or mutagenic techniques tend to result in large swaths of genes being swapped or altered. GM technology, in contrast, enables scientists to insert into a plant's genome a single gene (or a few of them)—including genes isolated from another species of plant or even from a bacterium, virus or animal. Supporters argue that the precise control offered by genetic technology makes it much less likely to produce surprises. Most plant molecular biologists also say that in the highly unlikely case that an unexpected health threat emerged from a new GM plant, scientists would quickly identify and eliminate it. "We know where the gene goes and can measure the activity of every single gene around it," Goldberg says. "We can show exactly which changes occur and which

IN BRIEF

The vast majority of the research on genetically modified (GM) crops suggests that they are safe to eat and that they have the potential to feed millions of people worldwide who currently go hungry. **Yet not all criticisms** of GM are so easily rejected, and pro-GM scientists are often dismissive and even unscientific in their rejection of the counterevidence. **A careful analysis** of the risks and benefits argues for expanded deployment *and* safety testing of GM crops.

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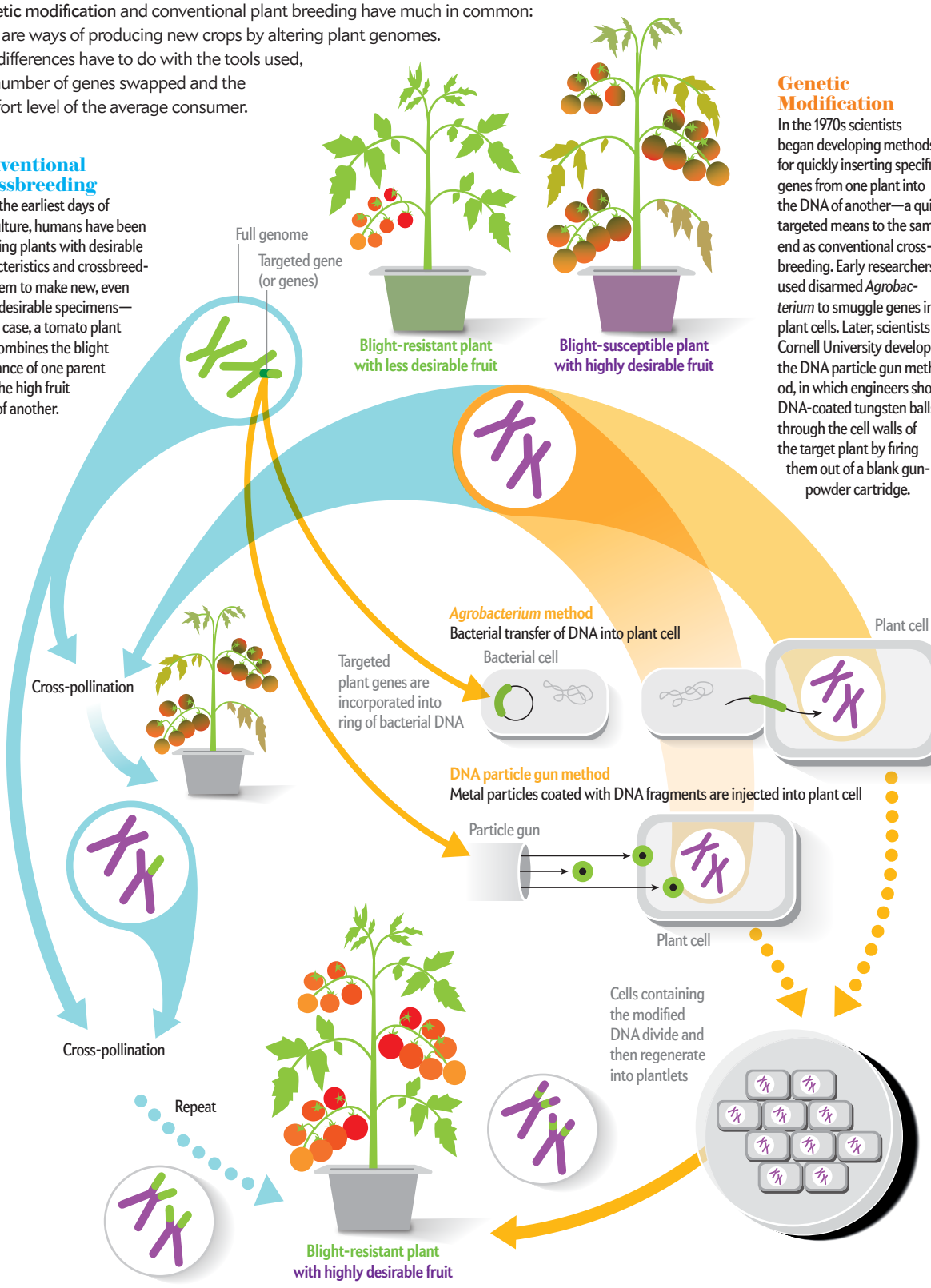
BASICS

How to Build a Better Plant

Genetic modification and conventional plant breeding have much in common: both are ways of producing new crops by altering plant genomes. The differences have to do with the tools used, the number of genes swapped and the comfort level of the average consumer.

Conventional Crossbreeding

Since the earliest days of agriculture, humans have been selecting plants with desirable characteristics and crossbreeding them to make new, even more desirable specimens—in this case, a tomato plant that combines the blight resistance of one parent with the high fruit yield of another.


Full genome
Targeted gene (or genes)
Blight-resistant plant with less desirable fruit
Blight-susceptible plant with highly desirable fruit
Cross-pollination
Agrobacterium method
Bacterial transfer of DNA into plant cell
Bacterial cell
Targeted plant genes are incorporated into ring of bacterial DNA
Plant cell
DNA particle gun method
Metal particles coated with DNA fragments are injected into plant cell
Particle gun
Plant cell
Cross-pollination
Cells containing the modified DNA divide and then regenerate into plantlets
Repeat
Blight-resistant plant with highly desirable fruit

Genetic Modification

In the 1970s scientists began developing methods for quickly inserting specific genes from one plant into the DNA of another—a quick, targeted means to the same end as conventional crossbreeding. Early researchers used disarmed *Agrobacterium* to smuggle genes into plant cells. Later, scientists at Cornell University developed the DNA particle gun method, in which engineers shoot DNA-coated tungsten balls through the cell walls of the target plant by firing them out of a blank gunpowder cartridge.

Illustration by Jen Christiansen

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don't." [For more on how GM plants are analyzed for health safety, see "The Risks on the Table," by Karen Hopkin; SCIENTIFIC AMERICAN, April 2001.]

And although it might seem creepy to add virus DNA to a plant, doing so is, in fact, no big deal, proponents say. Viruses have been inserting their DNA into the genomes of crops, as well as humans and all other organisms, for millions of years. They often deliver the genes of other species while they are at it, which is why our own genome is loaded with genetic sequences that originated in viruses and nonhuman species. "When GM critics say that genes don't cross the species barrier in nature, that's just simple ignorance," says Alan McHughen, a plant molecular geneticist at U.C. Riverside. Pea aphids contain fungi genes. Triticale is a century-plus-old hybrid of wheat and rye found in some flours and breakfast cereals. Wheat itself, for that matter, is a cross-species hybrid. "Mother Nature does it all the time, and so do conventional plant breeders," McHughen says.

Could eating plants with altered genes allow new DNA to invade our own? It is theoretically possible but hugely improbable. Outside of the DNA in a few well-known foodborne-disease viruses, scientists have never found genetic material that could survive a trip through the human gut and infect cells. Besides, we are routinely exposed to—we even consume—the viruses and bacteria whose genes end up in GM foods. The bacterium *Bacillus thuringiensis,* for example, which produces proteins fatal to insects, is sometimes enlisted as a natural pesticide in organic farming. "We've been eating this stuff for thousands of years," Goldberg says.

In any case, proponents contend, people have consumed trillions of meals containing genetically modified ingredients over the past few decades. Not a single verified case of illness has ever been attributed to the genetic alterations. Mark Lynas, a prominent anti-GM activist who publicly switched to strongly supporting the technology in 2012, has pointed out that every single news-making food disaster on record has been attributed to non-GM crops, such as the *Escherichia coli*–infected organic bean sprouts that killed 53 people in Europe in 2011.

Critics often disparage U.S. research on the safety of genetically modified foods, which is often funded or even conducted by GM seed producers, such as Monsanto. But much research on the subject comes from the European Commission, the administrative body of the E.U., which cannot be so easily dismissed as an industry tool. The commission has funded more than 130 research projects, carried out by over 500 independent teams, on the safety of GM crops. None of those studies found any special risks from GM crops.

Plenty of other credible groups have arrived at the same conclusion. Gregory Jaffe, director of biotechnology at the Center for Science in the Public Interest, a science-based consumer-watchdog group in Washington, D.C., takes pains to note that the center has no official stance, pro or con, with regard to genetically modifying food plants. Yet Jaffe insists the scientific record is clear. "Current GM crops are safe to eat and can be grown safely in the environment," he says. The American Association for the Advancement of Science, the American Medical Association and the National Academy of Sciences have all unreservedly backed GM crops. The U.S. Food and Drug Administration, along with its counterparts in several other countries, has repeatedly reviewed large bodies of research and concluded that GM crops pose no unique health threats. Dozens of review studies carried out by academic researchers have backed that view.

THE MIDDLE GROUND IN THIS DEBATE: CONTINUE DISTRIBUTION OF GM FOODS WHILE STEPPING UP THE TESTING OF *ALL* CROPS.

Opponents of genetically modified foods point to a handful of studies indicating possible safety problems. But reviewers have dismantled almost all of those reports. For example, a 1998 study by plant biochemist Árpád Pusztai, then at the Rowett Institute in Scotland, found that rats fed a GM potato suffered from stunted growth and changes to their immune systems. But the potato was not intended for human consumption—it was, in fact, designed to be toxic for research purposes. The Rowett Institute later deemed the experiment so sloppy that it refuted the findings and charged Pusztai with misconduct.

Similar stories abound. In 2012 a team led by Gilles-Éric Séralini, a researcher at the University of Caen Lower Normandy in France, found that rats eating a common type of GM corn contracted cancer at an alarmingly high rate. But Séralini has long been an anti-GM campaigner, and critics charged that in his study he relied on a strain of rat that too easily develops tumors, did not use enough rats, did not include proper control groups and failed to report many details of the experiment, including how the analysis was performed. After a review, the European Food Safety Authority dismissed the study's findings. Several other European agencies came to the same conclusion. "If GM corn were that toxic, someone would have noticed by now," McHughen says. "Séralini has been refuted by everyone who has cared to comment."

Some scientists say the objections to GM food stem from politics rather than science—that they are motivated by an objection to large multinational corporations having enormous influence over the food supply. Invoking risks from genetic modification, they argue, just provides a convenient way of whipping up the masses against industrial agriculture. "This has nothing to do with science," Goldberg says. "It's about ideology." Former anti-GM activist Lynas agrees. He recently went as far as labeling the anti-GM crowd "explicitly an antiscience movement."

PERSISTENT DOUBTS

NOT ALL OBJECTIONS to genetically modified foods are so easily dismissed, however. Long-term health effects can be subtle and nearly impossible to link to specific changes in the environment. Scientists have long believed that Alzheimer's disease and many cancers have environmental components, but few would argue we have identified all of them.

And opponents say that it is not true that the GM process is less likely to cause problems simply because fewer, more clearly identified genes are switched. David Schubert, an Alzheimer's researcher who heads the Cellular Neurobiology Lab-

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oratory at the Salk Institute for Biological Studies in La Jolla, Calif., asserts that a single, well-characterized gene can still settle in the target plant's genome in many different ways. "It can go in forward, backward, at different locations, in multiple copies, and they all do different things," he says. And as U.C.L.A.'s Williams notes, a genome often continues to change in the successive generations after the insertion, leaving it with a different arrangement than the one intended and initially tested. There is also the phenomenon of "insertional mutagenesis," Williams adds, in which the insertion of a gene ends up quieting the activity of nearby genes.

True, the number of genes affected in a GM plant most likely will be far, far smaller than in conventional breeding techniques. Yet opponents maintain that because the wholesale swapping or alteration of entire packages of genes is a natural process that has been happening in plants for half a billion years, it tends to produce few scary surprises today. Changing a single gene, on the other hand, might turn out to be a more subversive action, with unexpected ripple effects, including the production of new proteins that might be toxins or allergens.

Opponents also point out that the kinds of alterations caused by the insertion of genes from other species might be more impactful, more complex or more subtle than those caused by the intraspecies gene swapping of conventional breeding. And just because there is no evidence to date that genetic material from an altered crop can make it into the genome of people who eat it does not mean such a transfer will never happen—or that it has not already happened and we have yet to spot it. These changes might be difficult to catch; their impact on the production of proteins might not even turn up in testing. "You'd certainly find out if the result is that the plant doesn't grow very well," Williams says. "But will you find the change if it results in the production of proteins with long-term effects on the health of the people eating it?"

It is also true that many pro-GM scientists in the field are unduly harsh—even unscientific—in their treatment of critics. GM proponents sometimes lump every scientist who raises safety questions together with activists and discredited researchers. And even Séralini, the scientist who found high cancer rates for GM-fed rats, has his defenders. Most of them are nonscientists, or retired researchers from obscure institutions, or nonbiologist scientists, but the Salk Institute's Schubert also insists the study was unfairly dismissed. He says that as someone who runs drug-safety studies, he is well versed on what constitutes a good-quality animal toxicology study and that Séralini's makes the grade. He insists that the breed of rat in the study is commonly used in respected drug studies, typically in numbers no greater than in Séralini's study; that the methodology was standard; and that the details of the data analysis are irrelevant because the results were so striking.

Schubert joins Williams as one of a handful of biologists from respected institutions who are willing to sharply challenge the GM-foods-are-safe majority. Both charge that more scientists would speak up against genetic modification if doing so did not invariably lead to being excoriated in journals and the media. These attacks, they argue, are motivated by the fear that airing doubts could lead to less funding for the field. Says Williams: "Whether it's conscious or not, it's in their interest to promote this field, and they're not objective."

Both scientists say that after publishing comments in journals questioning the safety of GM foods, they became the victims of coordinated attacks on their reputations. Schubert says that researchers who turn up results that might raise safety questions avoid publishing their findings out of fear of repercussions. "If it doesn't come out the right way," he says, "you're going to get trashed."

There is evidence to support that charge. In 2009 *Nature* detailed the backlash to a reasonably solid study published in the *Proceedings of the National Academy of Sciences USA* by researchers from Loyola University Chicago and the University of Notre Dame. (*Scientific American* is part of Nature Publishing Group.) The paper showed that GM corn seemed to be finding its way from farms into nearby streams and that it might pose a risk to some insects there because, according to the researchers' lab studies, caddis flies appeared to suffer on diets of pollen from GM corn. Many scientists immediately attacked the study, some of them suggesting the researchers were sloppy to the point of misconduct.

A WAY FORWARD

THERE IS A MIDDLE GROUND in this debate. Many moderate voices call for continuing the distribution of GM foods while maintaining or even stepping up safety testing on new GM crops. They advocate keeping a close eye on the health and environmental impact of existing ones. But they do not single out GM crops for special scrutiny, the Center for Science in the Public Interest's Jaffe notes: *all* crops could use more testing. "We should be doing a better job with food oversight altogether," he says.

Even Schubert agrees. In spite of his concerns, he believes future GM crops can be introduced safely if testing is improved. "Ninety percent of the scientists I talk to assume that new GM plants are safety-tested the same way new drugs are by the FDA," he says. "They absolutely aren't, and they absolutely should be."

Stepped-up testing would pose a burden for GM researchers, and it could slow down the introduction of new crops. "Even under the current testing standards for GM crops, most conventionally bred crops wouldn't have made it to market," McHughen says. "What's going to happen if we become even more strict?"

That is a fair question. But with governments and consumers increasingly coming down against GM crops altogether, additional testing may be the compromise that enables us to benefit from those crops' significant advantages. SA

David H. Freedman has been covering science, business and technology for 30 years. His most recent book, *Wrong*, explores the forces that cause scientists and other experts to mislead us.

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TECHNOLOGY

INSIDE THE MEAT LAB

A handful of scientists aim to satisfy the world's growing appetite for steak without wrecking the planet. The first step: grab a petri dish

By Jeffrey Bartholet

IT IS NOT UNUSUAL FOR VISIONARIES TO BE IMPASSIONED, IF NOT FANATICAL, AND WILLEM VAN EELEN was no exception. Before he died in February at age 91, van Eelen looked back on his extraordinary life. He was born in Indonesia when it was under Dutch control, the son of a doctor who ran a leper colony. As a teenager, he fought the Japanese in World War II and spent several years in prisoner-of-war camps. The Japanese guards used prisoners as slave labor and starved them. "If one of the stray dogs was stupid enough to go over the wire, the prisoners would jump on it, tear it apart and eat it raw," van Eelen recalled in a 2011 interview. "If you looked at my stomach then, you saw my spine. I was already dead." The experience triggered a lifelong obsession with nutrition and the science of survival.

Photograph by Kevin Van Aelst

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One obsession led to another. After the Allies liberated Indonesia, van Eelen studied medicine at the University of Amsterdam. A professor showed the students how he had been able to get a piece of muscle tissue to grow in the laboratory. This demonstration inspired van Eelen to consider the possibility of growing edible meat without having to raise or slaughter animals. Imagine, he thought, protein-rich food that could be grown like crops, no matter what the climate or other environmental conditions, without killing any living creatures.

If anything, the idea is more potent now. The world population was a little more than two billion in 1940, and global warming was not a concern. Today the planet is home to three times as many people. According to a 2013 report by the United Nations Food and Agriculture Organization, the livestock business accounts for about 14.5 percent of all anthropogenic greenhouse gas emissions—an even larger contribution than the global transportation sector [see "The Greenhouse Hamburger," on page 108]. The organization has projected that worldwide meat consumption will grow by 73 percent between 2010 and 2050.

Meat grown in bioreactors—instead of raised on farms—could help alleviate planetary stress. In 2010 Hanna Tuomisto, then at the University of Oxford, coauthored a study of the potential environmental impacts of cultured meat. The study found that such production, if scientists grew the muscle cells in a culture of cyanobacteria hydrolysate (a bacterium cultivated in ponds), would involve "approximately 35 to 60 percent lower energy use, 80 to 95 percent lower greenhouse gas emissions and 98 percent lower land use compared to conventionally produced meat products in Europe."

As it is, 30 percent of the earth's ice-free land is used for grazing livestock and growing animal feed. If cultured meat were to become viable and widely consumed, much of that land could be used for other purposes, including new forests that would pull carbon out of the air.

TEN CELLS COULD GROW INTO 50,000 METRIC TONS OF MEAT IN JUST TWO MONTHS. ONE SUCH CELL LINE WOULD BE SUFFICIENT TO FEED THE WORLD.

Meat would no longer have to be shipped around the globe, because production sites could be located close to consumers. Some proponents imagine small urban meat labs selling their products at street markets that cater to locavores.

THE ONLY CHOICE LEFT

EVEN WINSTON CHURCHILL thought in vitro meat was a good idea. "Fifty years hence, we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing by growing these parts separately under suitable medium," he predicted in a 1932 book, *Thoughts and Adventures*. For most of the 20th century, however, few took the idea seriously.

Van Eelen did not let it go. He worked all kinds of jobs—selling newspapers, driving a taxi, making dollhouses. He established an organization to help underprivileged kids and owned art galleries and cafes. He wrote proposals for in vitro meat production and eventually plowed much of his earnings into applying for patents. Together with two partners, he won a Dutch patent in 1999, then other European patents and, eventually, two U.S. patents.

In 2005 van Eelen and others finally convinced the Dutch Ministry of Economic Affairs to pledge €2 million ($2.5 million) to support in vitro meat research in the Netherlands—the largest government grant for such research to date.

By that time, an American scientist had already succeeded in growing a piece of fish filet in a lab. Using a small grant from NASA, which was interested in developing food sources for deep-space voyages, Morris Benjaminson removed skeletal muscle from a common goldfish and grew it outside the fish's body. Then an associate briefly marinated the explants in olive oil, chopped garlic, lemon and pepper, covered them in bread crumbs and deep-fried them. "A panel of female colleagues gave it a visual and sniff test," says Benjaminson, now an emeritus professor at Touro College in Bay Shore, N.Y. "It looked and smelled pretty much the same as any fish you could buy at the supermarket." But NASA, apparently convinced there were easier ways to provide protein to astronauts on long deep-space voyages, halted funding for Benjaminson's research.

In the Netherlands, van Eelen and Henk P. Haagsman, a scientist at Utrecht University, used their grant to fund a consortium to try to make meat from stem cells, which are able to generate a wide range of tissue types. They aimed to culture stem cells isolated from farm animals and then induce the cells to form skeletal muscle tissue. The team included a representative from meat company Meester Stegeman BV, then part of Sara Lee Corporation in Europe, as well as top scientists at three Dutch universities. Each university studied different aspects of in vitro meat production. Scientists at the University of Amsterdam focused on producing efficient growth media; a group at Utrecht worked on isolating stem cells, making them proliferate and coaxing them into muscle cells; and those at Eindhoven University of Technology attempted to "train" the muscle cells to grow larger.

The scientists made some progress. They were able to grow small, thin strips of muscle tissue in the lab—stuff that looked like bits of scallop and had the chewy texture of calamari—but several obstacles remained to commercial-scale production. "We gained knowledge, we

IN BRIEF

Scientists have grown beef and fish in laboratories by culturing partially differentiated stem cells that give rise to muscle. The meat was suitable for consumption.

Only small amounts of meat—enough to make one hamburger—have been cultured so far. But if work now under way succeeds in scaling up the technology, cultured meat could provide high-protein food sources free of the environmental, ethical and food-safety issues that surround large-scale livestock operations.

Further progress has been slow, however, in part because scientists have had to rely heavily on private sources of funding for research and development.

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knew a lot more, but we still didn't have [something that tasted like] a T-bone steak that came from a petri dish," says Peter Verstrate, who represented Meester Stegeman in the consortium and now works as a consultant. In time, the Dutch money ran out.

Van Eelen fumed in 2011 that one scientist involved was "stupid" and others just milked him and the Dutch government for money. "I don't know what they did in four years—talking, talking, talking—every year taking more of the money," he said.

The scientists respond that van Eelen never understood the scale of the challenge. "He had a naive idea that you could put muscle cells in a petri dish and they would just grow, and if you put money into a project, you'd have meat in a couple of years," says Bernard Roelen, a cell biologist who worked on the project at Utrecht.

Van Eelen was not the only one who imagined a revolution. In 2005 researchers published the first peer-reviewed article on cultured meat in the journal *Tissue Engineering*. The authors included Jason G. Matheny, cofounder of the lab-produced meat advocacy group New Harvest. He has no illusions that the path will be easy. "Tissue engineering is really hard and extremely expensive right now," he says. "To enjoy market adoption, we mainly need to solve the technical problems that increase the cost of engineered meat." That will take money, he notes, and few governments or organizations have been willing to commit necessary funding.

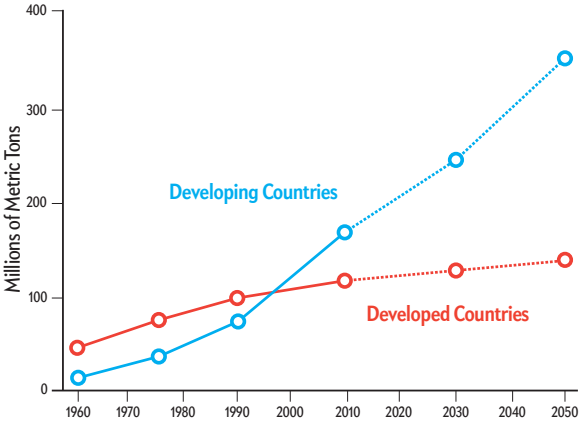
To the researchers involved, that failure seems shortsighted. "I think [in vitro meat] will be the only choice left," says Mark J. Post, head of the physiology department at Maastricht University. "I'm very bold about this. I don't see any way you could still rely on old-fashioned livestock in the coming decades." In 2011 Post continued van Eelen's project by launching an ambitious attempt to culture enough beef to make a hamburger.

GLOBAL TRENDS

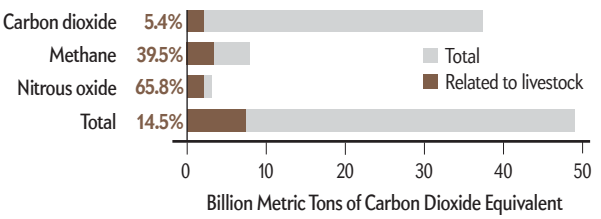
Meaty Problems

The rich world already eats a lot of meat; the developing world is catching up. One reason is that as more people move to cities, improved infrastructure means that meat can be kept cold throughout its journey from the slaughterhouse to the kitchen. Yet as demand for meat increases, so will the environmental consequences. Livestock farming already accounts for 14.5 percent of all anthropogenic greenhouse gas emissions.

Global Meat Consumption



Livestock's Current Contribution to Greenhouse Gas Emissions



SOURCES: UNITED NATIONS FAO (*historical consumption data*); *WORLD AGRICULTURE TOWARDS 2030/2050: THE 2012 REVISION*, BY NIKOS ALEXANDRATOS AND JELLE BRUINSMA, U.N. FAO, 2012 (*consumption projections*); *TACKLING CLIMATE CHANGE THROUGH LIVESTOCK: A GLOBAL ASSESSMENT OF EMISSIONS AND MITIGATION OPPORTUNITIES*, BY U.N. FAO, 2013, AND *CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE*, BY IPCC, 2014 (*emissions graph*)

ASSEMBLY REQUIRED

IN THEORY, an in vitro meat factory would work something like this: First, technicians would isolate embryonic or adult stem cells from a pig, cow, chicken or other animal. Then they would grow those cells in bioreactors, using a culture derived from plants. The stem cells would divide and redivide for months on end. Technicians would next instruct the cells to differentiate into muscle (rather than, say, bone or brain cells). Finally, the muscle cells would need to be "bulked up" in a fashion similar to the way in which animals build their strength by exercising.

But tissue engineers have come up against multiple problems. When stem cell lines proliferate for long periods, many cells suddenly decide on their own to differentiate. And of those cells that do wait for the external signal to differentiate, many do not turn into muscle as instructed. "If 10 cells differentiate, you want at least seven or eight to turn into muscle cells, not three or four," Roelen says. By 2011 only about half of the stem cells were turning to muscle on command.

The Utrecht scientists tried to extract and develop embryonic stem cell lines from pigs. Such cells would, in normal conditions, be able to duplicate every day for long periods, meaning 10 cells could grow into a staggering amount of potential meat in just two months: over 50,000 metric tons. "Culturing embryonic stem cells would be ideal for this purpose since these cells have an (almost) infinite self-renewal capacity," according to a 2009 report by the Utrecht team. "In theory, one such cell line would be sufficient to literally feed the world."

Such cell lines have been developed from mice, rats, rhesus monkeys and humans. But embryonic cells from farm animals have a tendency to differentiate quickly—and of their own accord—into specialized cells. The Utrecht team's porcine cells often veered toward "a neural lineage"—brains, not bacon.

Post chose to work with adult stem cells called muscle satellite cells, which exist within skeletal muscle and are largely preprogrammed to replace muscle fibers when they are injured or die off. Satellite cells do not proliferate as readily as embryonic cells do, but they form muscle more reliably.

Cost poses another barrier. The culture used to grow stem cells of any kind is very expensive. In 2011 Roelen estimated that cultured meat cost $50,000 a pound—and it was not acceptable to vegetarians, because the nutrient baths were derived from fetal calf or horse serum

Graphics by Jen Christiansen

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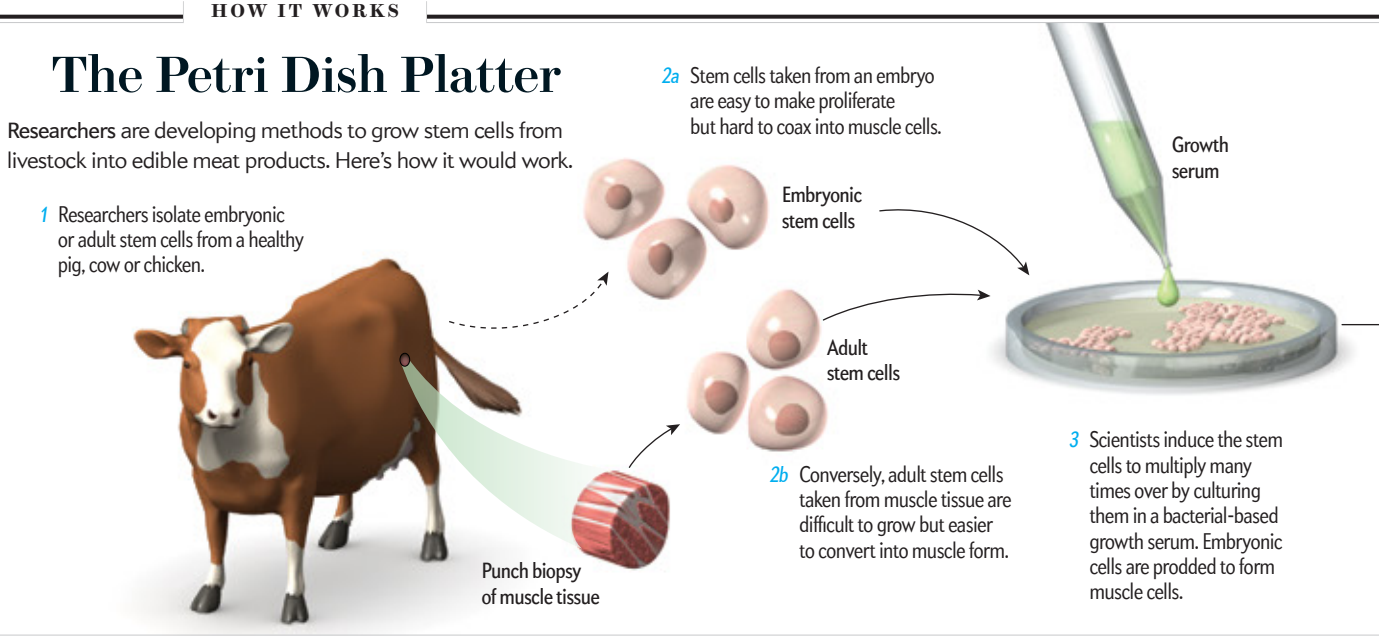
HOW IT WORKS

The Petri Dish Platter

Researchers are developing methods to grow stem cells from livestock into edible meat products. Here's how it would work.


1 Researchers isolate embryonic or adult stem cells from a healthy pig, cow or chicken.
Punch biopsy of muscle tissue
2a Stem cells taken from an embryo are easy to make proliferate but hard to coax into muscle cells.
Embryonic stem cells
2b Conversely, adult stem cells taken from muscle tissue are difficult to grow but easier to convert into muscle form.
Adult stem cells
Growth serum
3 Scientists induce the stem cells to multiply many times over by culturing them in a bacterial-based growth serum. Embryonic cells are prodded to form muscle cells.

taken from slaughtered animals. But scientists have since developed recipes for "chemically defined media" that include no animal products. They have also been able to genetically engineer plant cells to produce animal proteins that could be used to grow the meat. Both these types of media remain prohibitively expensive.

An algae-based medium may eventually work best because algae can produce the proteins and amino acids necessary to sustain cell life. But that, too, is costly—at least for now. Post has optimistically estimated that large-scale production of in vitro meat could lower the price to about $10 a pound and that coming advances in the technology will reduce costs further.

Once researchers are able to produce a big supply of muscle cells, they will need to keep the cells alive and bulk them up. It is possible now to assemble cells into a thin strip of tissue, but when the layer gets more than a few cell layers thick, parts of it start to die off. The cells need a constant flow of fresh nutrients to stay alive. In the body, these nutrients are delivered by the bloodstream, which also removes waste. Post is trying to develop a three-dimensional system that delivers such nutrients.

Meanwhile he has demonstrated one way to add bulk to the muscle cells: exercise them. "If you take your cast off after a bone break, it scares you: the muscles are gone," he says. "But within a couple of weeks they're back. We need to replicate that process." Scientists have tried stimulating the tissue with electrical pulses. But that is costly and inefficient, bulking up the cells by only about 10 percent.

Post found some success with a different approach. He provides sticking points made of Velcro to which the developing tubules of muscle can attach. When anchored on either end, the fibers develop tension on their own and expand in size. But at this stage, he says, "we're not looking at Schwarzenegger muscle cells."

Post has described another, more complex method that might work even better. The body naturally stimulates muscle growth with micropulses of acetylcholine and other chemicals—which are inexpensive to supply. "The trick is to do it in very, very short pulses," Post says. The hurdles to that are technological, not scientific.

Breakthroughs in all these areas will take money, which so far has come in unpredictable bursts, mainly from private sources. In 2008 People for the Ethical Treatment of Animals (PETA) offered $1 million to anyone who could grow commercially viable chicken in a lab by 2012. The deadline was later extended to 2014, but the money still went unclaimed. More seriously, the European Union has funded studies on the social and moral questions related to in vitro meat, Google co-founder Sergey Brin gave Post's lab $325,000 to try to create a lab-grown hamburger, and a Brooklyn-based start-up called Modern Meadow recently raised $10 million in venture capital to fund its quest to make cultured leather and meat.

THE ICK FACTOR

SOME SEE SOCIAL ACCEPTANCE as the biggest barrier of all to producing in vitro meat on a commercial scale. "I've mentioned cultured meat to scientists, and they all think, 'great idea,'" says Tuomisto, who now works for the European Commission. "When I talk to nonscientists, they are more afraid of it. It sounds scary. Yet it's basically the same stuff: muscle cells. It's just produced differently."

Cor van der Weele of Wageningen University has been investigating the philosophical aspects of cultured meat (for example, is lab-grown meat a moral imperative or morally repugnant, or some combination of the two?). She has been intrigued by the emotional reactions that some people have toward the idea. "We call it the 'yuck response,'" she says. "People initially think that it might be something contaminated or disgusting."

But that perception can change quickly, van der Weele observes. She notes that people often associate cultured meat with two other ideas: genetically modified foods—which are often seen, particularly in Europe, as a dangerous corporate scheme to dominate or control the food

Illustration by Emily Cooper

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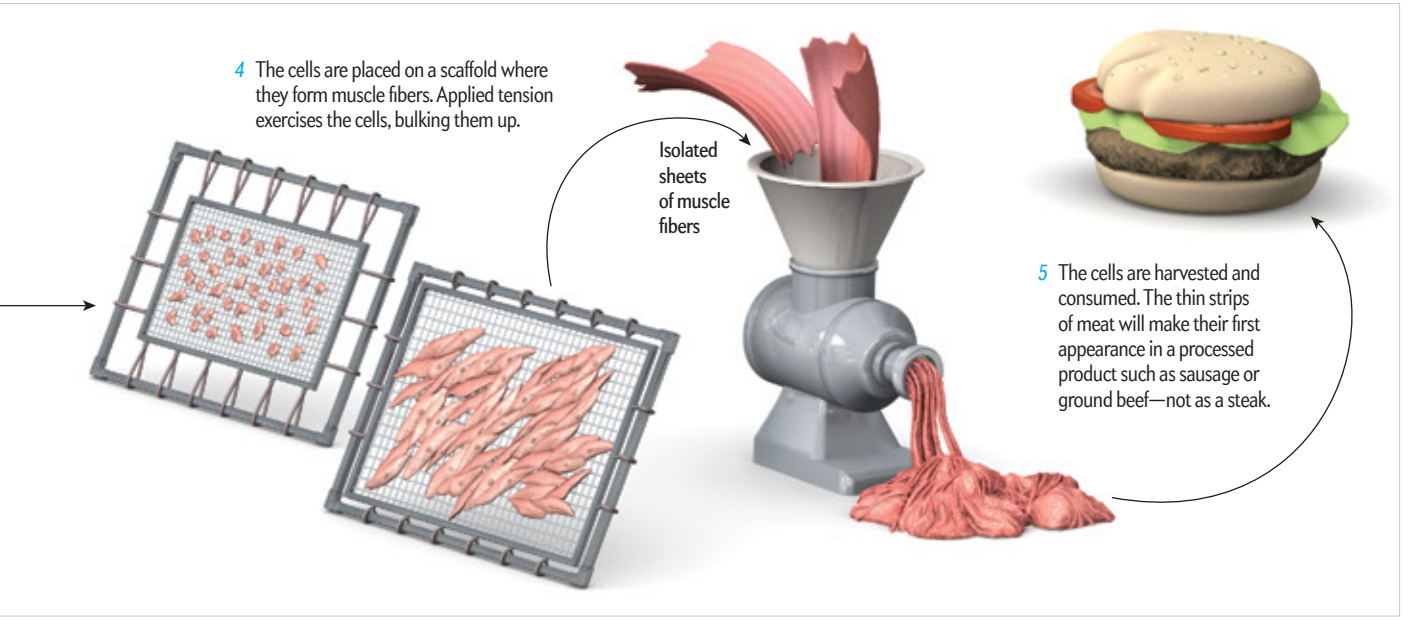
4 The cells are placed on a scaffold where they form muscle fibers. Applied tension exercises the cells, bulking them up.
Isolated sheets of muscle fibers
5 The cells are harvested and consumed. The thin strips of meat will make their first appearance in a processed product such as sausage or ground beef—not as a steak.

supply—and negative perceptions of the meat industry in general, with its factory farms, disease and mistreatment of animals. Once people realize that cultured meat is not genetically modified and could be a clean, animal-friendly alternative to factory farms, she says, "the scared, very negative response is often very fleeting."

Such observations are only anecdotal, of course. One of the European studies observed that many people initially reacted with revulsion at the notion of cultured meat but then developed more ambivalent feelings as they thought through the potential pros and cons both personally and to society at large. Further studies are under way to determine ways to frame the issue that might enhance consumer interest. Proponents imagine a day when governments will levy special environmental taxes on meat produced from livestock or when consumers will be able to opt for in vitro meat that is labeled "cruelty-free."

"I don't think you want to know about the hygienic conditions in the majority of slaughterhouses in the U.S. or the efficiency of euthanasia," Post says. Another outbreak of disease—like mad cow or bird flu—could make cultured meat seem all the more appetizing. "We are far from what we eat," Roelen says. "When we're eating a hamburger, we don't think, 'I'm eating a dead cow.' And when people are already so far from what they eat, it's not too hard to see them accepting cultured meat."

Post's bold scheme to create a hamburger in vitro culminated in a highly publicized demonstration in August 2013, when he, food scientist Hanni Rützler and food writer Josh Schonwald shared bites of the first cultured patty. The taste was bland but not disgusting, according to Schonwald. The lack of fat was noticeable, all agreed.

The fact that it took three months of effort and more than $300,000 to produce a single, mediocre-tasting patty—which consisted of roughly 10,000 short strips totaling 15 billion cells—suggests that cultured meat is not likely to turn up in supermarkets anytime soon.

"It's basically a stunt to generate more funds," Post acknowledged even as the project was just starting. "We're trying to prove to the world we can make a product out of this." But can cultured meat be made to taste like the conventional variety?

"I think so," Roelen says. "Most of the taste in a chicken nugget or a sausage is artificially made. Salt and all kinds of other things are added to give it taste."

Van Eelen, who regarded himself as "the godfather of in vitro meat," was not a fan of such stunts. He was a diehard idealist and argued that it is important to launch the in vitro revolution with meat that looks, smells and tastes just like anything you would buy off the farm.

In recent years van Eelen also saw that time was running out to realize a dream that he had pursued nearly his entire life. "Every time you talk to him, he's speaking about someone else he's found who will be the top scientist who will solve his problems," Roelen said in 2011. "I can understand his point of view. But I can't change the laws of the universe." SA

Jeffrey Bartholet is a veteran foreign correspondent and former Washington bureau chief for *Newsweek* magazine.

MORE TO EXPLORE

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FOOD TECHNOLOGY

BUILDING TASTIER FRUITS AND VEGGIES*

Making modern supermarket produce so big and hardy drained a lot of its flavor. Scientists now have the technology to bring it back—without genetic engineering

By Ferris Jabr

THE MODERN SUPERMARKET PRODUCE AISLE IS FULL OF VISUal illusions. The strawberries are plump and glistening; the tomatoes smooth-skinned and lustrous; the melons firm and brightly colored—yet all too often devoid of flavor. We have no one to blame for these bland beauties but ourselves. By selectively breeding crops to be as prodigious as possible and to survive weeks of shipping and storage in dark, cool conditions, we have sapped flavor, aroma and nutrition from our food.

Photographs by Dan Saelinger

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Consider the dilemma that cantaloupes presented to plant breeders. To enjoy a cantaloupe's full flavor, you must pick and eat it at peak ripeness, before it goes too soft. Toward the later stages of a cantaloupe's development, a burst of the hormone ethylene causes the fruit to ripen and soften quite quickly. This speedy puberty made transporting cantaloupes across states or from one country to another problematic: even on ice, the melons turned to mush by the voyage's end. So plant breeders decreased the levels of ethylene in cantaloupes intended for long-distance shipping by cross-pollinating only melons that naturally produced the lowest amounts of the hormone. Without a strong spurt of ethylene, the melons stay firm on the trip from field to produce aisle, but the chemical reactions that produce a ripe melon's aroma and taste never happen.

Breeders have had some success in overcoming this predicament. In the 1990s Dominique Chambeyron—a plant breeder employed by the Dutch De Ruiter Seeds Group—managed to create a variety of small, striped cantaloupe that retained both its firmness and flavor for weeks after it was harvested. Known as Melorange, this cultivar is grown in Central America and shipped to Sam's Club and other select chain stores in the U.S. between December and April, when it is too cold to grow cantaloupes locally. I tried a slice of one last year: it had a dense texture and a splutter of flavor and aroma so robust, it bordered on spicy. Unfortunately, the kind of traditional breeding responsible for the Melorange relies an awful lot on serendipity. It can take more than a decade to perfect a consistently impressive new cultivar. Breeders must cross-pollinate plants over and over, hoping that some of the offspring will inherit the right characteristics. And they generally have to wait for the plants to grow and produce ripe fruit to find out. Much of what they reap is way off the mark and entirely unusable.

Genetics has recently offered an alternative path. At Monsanto, which acquired De Ruiter in 2008, Jeff Mills and his colleagues are able to predict the quality of a cantaloupe plant's eventual fruit before they ever put a single seed in the ground. First, Mills and his team pinpointed the melon genes underlying Melorange's unique combination of flavor and firmness. They can look for these genetic "markers" in cantaloupe seeds with help from a group of cooperative and largely autonomous robots.

I saw many of these machines in action when I visited Monsanto's molecular breeding laboratory at its vegetable research and development headquarters in Woodland, Calif., in November 2013. A seed chipper shaves off a sliver of a seed for DNA analysis, leaving the rest of the kernel unharmed and suitable for sowing in a greenhouse or field. Another robot extracts the DNA from that tiny bit of seed and adds the necessary molecules and enzymes to chemically glue fluorescent tags to the relevant genes, if they are there. Yet another machine amplifies the number of these glowing tags to measure the light they emit and determine whether a gene is present.

Such techniques, known as marker-assisted breeding, are not brand-new, but they have enabled unprecedented feats of produce perfectionism in the past 10 years because genetic sequencing has become so much faster and cheaper. Monsanto's seed chippers can run 24 hours a day, and the entire system can deliver results to breeders within two weeks. In the past 10 years breeders at both private companies and universities have managed to create a cornucopia of more flavorful, colorful, shapely and nutritious fruits and vegetables, some of which are already available at grocery stores and farmers' markets. In addition to increasingly appetizing melons, the bounty includes broccoli that brims with even more nutrients than usual, truly succulent strawberries, and tomatoes that please both the eye and the tongue.

"The impact of genomics on plant breeding is almost beyond my comprehension," says Shelley Jansky, a potato breeder who works for both the U.S. Department of Agriculture and the University of Wisconsin–Madison. "I had a grad student here [in 2009] who spent three years trying to identify DNA sequences associated with disease resistance. After hundreds of hours in the lab, he ended up with 18 genetic markers. Now I have grad students who can get 8,000 markers for each of 200 individual plants within a matter of weeks."

All this talk of DNA analysis may sound suspiciously like genetic engineering—the gene-editing technique that creates genetically modified organisms (GMOs). But it is not. It is a completely non-GMO technology. In fact, that is one of the main reasons it is so attractive to researchers and to seed companies such as Monsanto.

SOWING CHANGE

PEOPLE HAVE BEEN CHANGING PLANTS to suit their purposes for at least 9,000 years. Just about every fruit and vegetable we eat is a domesticated species that we have transformed through decades of artificial selection and breeding: saving seeds only from plants with the most desirable characteristics and deliberately mating one plant with another to create novel combinations of traits. In this way, our ancestors turned a scrawny grass named teosinte into tall, plump-eared corn and molded a single species of wild cabbage into broccoli, Brussels sprouts, cauliflower and kale.

By the 1980s scientists had devised a much more exacting way of changing a plant's DNA: genetic engineering, which involves adding, removing or otherwise directly altering genes in a plant using lab tools. GMOs first appeared on the market in the U.S. in the 1990s. Although more than 70 percent of processed foods in the U.S. contain ingredients made

IN BRIEF

Creating crops that meet the practical demands of industrial agriculture resulted in supermarket fruits and vegetables that often lack the full flavor and nutrition of older varieties.

Instead of improving such crops by using genetic engineering, scientists are turning to marker-assisted breeding, which combines traditional plant breeding with ever speedier DNA analysis.

Advanced backcrossing has yielded highly flavorful tomato cultivars that also can tolerate shipping. And the method produces a broccoli variety having higher levels of some nutrients.

Plant breeders at public universities have traditionally donated such improved crops to farmers. Now they must license the seeds to a handful of large private companies.

STYLING FOR TOMATO AND CANTALOUPE BY BIRTE VON KAMPEN

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from GMO corn, soybeans and canola, very few of the fresh vegetables and fruits sold in supermarkets have been genetically engineered. Exceptions include virus-resistant papaya, plum and squash, as well as pest-resistant sweet corn.

One reason that so few fresh fruits and veggies are GMOs is that, on the whole, they are far less profitable and less widely grown than the country's biggest crops: corn, soybeans, hay, wheat, cotton, sorghum and rice. When it comes to fruits, veggies and other so-called specialty crops, seed companies are not as motivated to deal with the burdensome and costly safety tests and federal regulatory procedures required to approve a GMO for sale.

The other big hurdle to GMO fruits and vegetables is public opposition. Universities and seed companies know that introducing new GMOs to the produce aisle today could ignite a furor among the segment of the U.S. population opposed to what they believe are "Frankenfoods." Most shoppers remain oblivious to the few genetically engineered fruits and veggies already in stores because they are usually not labeled as such.

In the past decade marker-assisted breeding has become an increasingly viable way to improve fruits and vegetables while circumventing this controversy, especially as genetic technologies have improved and scientists have continued to sequence the genomes of more and more crop plants. In particular, the marriage of traditional breeding and DNA analysis is helping breeders turn their attention toward qualities of food that are important to consumers. "Asking what the consumer wants sounds really obvious, but it's not," says Harry J. Klee, a tomato breeder at the University of Florida. Instead, he says, you almost always see breeders prioritizing the needs of farmers or food distributors.

A perfect example is the classic supermarket tomato. For decades experts have regarded the balance of acids and sugars in a tomato as the primary factor that determines whether we enjoy its taste. In general, people like tomatoes on the sweet side. But most breeders have not been chiefly concerned with flavor. With large-scale commercial growers in mind, breeders have instead favored tomato plants producing lots of smooth, hardy fruit that remain plump on the often long journey to the grocery. The more tomatoes a plant makes, however, the fewer sugars it can give to each one. Typical supermarket tomatoes may look pretty, but they do not have enough sugar to satisfy our taste buds.

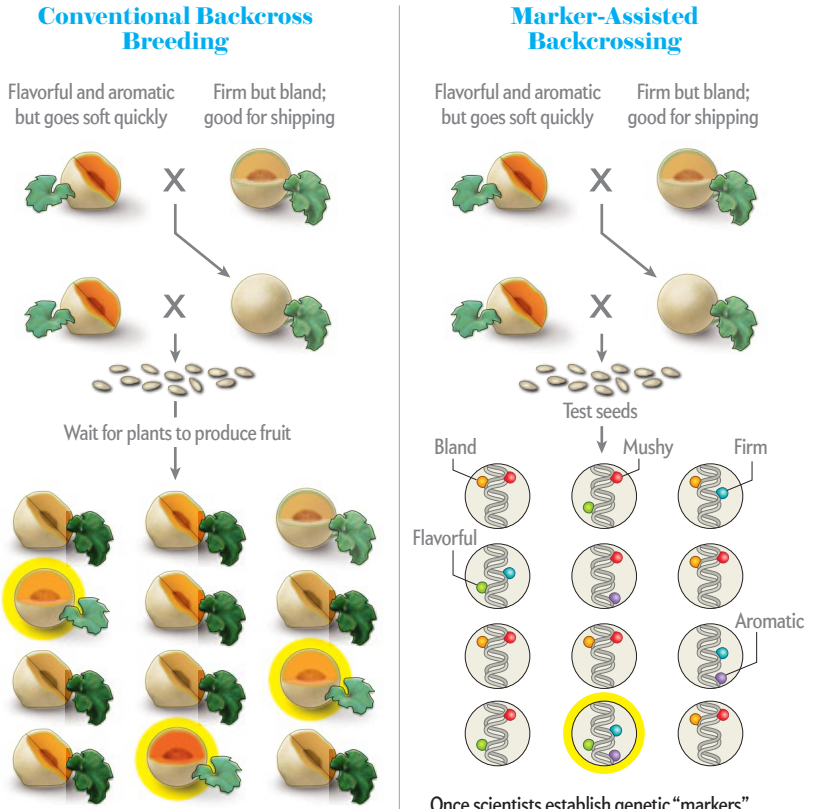
Klee is determined to rescue the industrial tomato from its current gustatory doldrums. Through a series of large taste tests, he has evaluated nearly 200 varieties of heirloom tomatoes—older cultivars preserved by small groups of farmers and gardeners and sold at some grocery stores and farmers' markets. Heirlooms are known for their vibrant colors and fantastic flavor, but their skin easily cracks and scars, they go soft quickly, and they come from plants that do not make enough fruit to meet the demands of large commercial farmers.

In his research, Klee has learned that many heirlooms are tastier than standard tomatoes not because they have more sugar but because they are chockfull of a much more complex component of flavor: pungent chemicals known as volatile organic compounds that waft off plants and into our nostrils (think: freshly cut grass or the alluring smell of citrus). In a 2012 study Klee and his colleagues discovered that people actually enjoy a tomato with moderate levels of

BASICS

Marker-Assisted Breeding

To improve a single crop, plant breeders usually have to play botanical matchmaker for many years, laboriously weeding out unwanted traits without losing desirable ones. Identifying the genes underlying those traits opens up the possibility of a much more efficient and precise process known as marker-assisted breeding.



Breeders typically have to wait a full season for experimental crops to mature before they can assess the quality of the produce and select the top contenders for continued breeding (*yellow highlighting*).

Once scientists establish genetic "markers" for different traits—such as flavor and firmness—they can analyze DNA extracted from seeds or the leaves of young plants and reveal ideal candidates (*yellow highlighting*) for breeding experiments long before harvesttime.

Graphic by Jen Christiansen

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sugar if it contains enough of an aromatic compound named geranial. Klee suspects that geranial and other volatiles not only give a tomato its scent but also magnify the fruit's innate sweetness. In follow-up studies, he created tomatoes that lacked geranial and other fragrant molecules. People did not like them. If a tomato had average to high sugar levels but no volatiles, volunteers did not perceive it as sweet.

Lately Klee has been trying to make hybrid plants that give growers and consumers the best of both tomato worlds, old and new. In the past four years he and his colleagues have mated the most delicious heirlooms they could find with modern conventional tomatoes to create crossbreeds that yield well, are firm and smooth-skinned, and taste great. Klee routinely stocks up on cheap electric toothbrushes, which he and his team use to gently but thoroughly rattle tomato flowers, gathering the pollen that falls off in test tubes so they can play matchmaker. All the while, the breeders have been using hole punches to collect bits of leaves and analyze the plants' DNA, looking for genetic patterns that correspond to high levels of volatiles, for instance, or flawless skin. "Genetic analysis has definitely informed crossing decisions," Klee says. The work accelerated greatly following the emergence of the tomato genome sequence in 2012, he says.

The University of Florida released two of these hybrids—Garden Gem and Garden Treasure—at the end of 2013. It is licensing them to seed companies for mass distribution. Although the hybrids do not yield quite as much as commercial tomatoes, they produce more than three times the number of fruit as their heirloom parents, they have tremendous flavor and they can survive a good deal of shipping. Klee's colleague Vance Whitaker is making good progress on a related project to enhance the pungency of supermarket strawberries, which have also gained size and durability at the expense of taste.

Another notable victim of distribution difficulties, along with cantaloupes and tomatoes, is broccoli. About 75 percent of broccoli harvested in the U.S. is grown in California. Broccoli adores cool weather and flourishes in the Salinas Valley's occasional fog blankets. When forced to endure hot, sticky summers in the Northeast, the vegetable produces gnarly heads

with buds of mismatched sizes. Each of the small buds that together make up broccoli's treetop dome is a flower that has not yet blossomed. Thomas Björkman of Cornell University and his colleagues discovered that during a critical period of its development, broccoli tracks how many hours of cool temperatures it enjoys and produces a uniform flowering head only if the tally is high enough. That is why broccoli grown on the East Coast might end up with an unattractive mix of nice, plump flower buds and dinky, almost imperceptible ones.

In early 2011 Björkman, Mark Farnham of the USDA and their many collaborators decided to breed a new kind of broccoli that would thrive in the eastern part of the country. In their lab's growth chamber, Björkman and his team have been subjecting broccoli to East Coast levels of heat and humidity, keeping seeds only from the plants that grow the most attractive flowering heads under these conditions. Although they have a lot of work ahead of them, they have already bred broccoli that can deal with a few more weeks of summer heat than the cultivars currently grown in the East. Meanwhile the researchers are searching the genomes of the various plants they grow, looking for genes that explain why some broccoli fares better than others. Finding them could shave years off the journey toward their ideal plant.

Breeding broccoli that stays beautiful in the heat is not just an exercise in aesthetics. It is also about getting tastier and

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more nutritious broccoli to farmers' markets and grocery stores. Fresh broccoli consumed the same day it has been harvested is different from typical supermarket fare, Björkman says—it is tender, with a mellow vegetative flavor, a hint of honeysuckle and no sharp aftertaste. Trucking broccoli from California to other parts of the country requires storing the vegetable on ice in the dark for days. With no light, photosynthesis halts, which means that cells stop making sugars. Rapidly dropping temperatures rupture cell walls, irrevocably weakening the plant's structure and diminishing its firmness. When the broccoli is thawed, various enzymes and molecules that escaped their cells bump into one another and trigger a sequence of chemical reactions, some of which degrade both nutritional and flavorful compounds. Giving farmers in the East broccoli they can grow and sell locally solves all these problems.

In a separate effort to boost the nutritional value of broccoli, Richard Mithen of the Institute of Food Research in England and his colleagues used marker-assisted breeding to raise levels of glucoraphanin, a compound that some evidence indicates may help fight bacteria and cancer. They have since licensed the resulting broccoli, called Beneforté, to Monsanto; you can find the florets at some Sam's Club, Harris Teeter and Stater Bros. stores.

SEEDING INNOVATION

TO GET THE GRANT that kicked off their initiative, Björkman and Farnham had to assure the USDA that seed companies were genuinely interested in this potential new regional market for broccoli by securing funding from the private sector. Monsanto, Syngenta and Bejo Seeds are contributing even though they are competitors. In theory, both seed companies and university researchers can benefit from such collaborations. During the research and development phase, they all share information and exchange seeds. Eventually, however, it is time for negotiations.

As is the case for Klee and his tasty tomatoes, Björkman hopes that once he and his colleagues get closer to their beauteous broccoli, a private company will license those seeds and produce them on a massive scale for commercial growers. Doing this requires substantial amounts of capital. Looking for genetic markers in individual plants may be getting cheaper all the time, but generating enormous quantities of seed and marketing it to farmers is still costly.

Some plant breeders worry that because giant seed companies have far more financial and technological resources than smaller firms and universities, true innovation will wither. "There's been a rather large decline in public-sector breeding programs as the technology has transferred into the private sector," says Irwin Goldman of the University of Wisconsin–Madison, who recently debuted flame-orange table beets with concentric gold stripes. "Some people argue that this transfer is a success for this country, but public breeding will do things that the private sector won't do—things that take too long or are too high risk."

Jack Juvik, who directs the plant-breeding center at the University of Illinois at Urbana-Champaign and first got into breeding in the 1970s, remembers when big companies were not nearly as dominant as they are today. "When I first started, there were a lot of smaller companies selling a lot of seeds, but they have all been basically bought out or driven out of the market by the mega companies. That has changed the whole texture of the industry," Juvik says. "Instead of having people at public institutions developing finished varieties, most of us design germplasm [seeds and cultivars] for big companies to work with. These large companies have the resources to do some good testing and make some really good varieties, but they end up controlling most of the germplasm and technology used to make it."

Goldman and his University of Wisconsin–Madison colleague Jack Kloppenburg belong to a group of breeders and farmers from around the country who are interested in creating the equivalent of open-source software for seeds—nonpatentable varieties that anyone can use. There is no precedent for such an arrangement in the 21st-century commercial seedscape, though. One potentially expensive option is for plant breeders to hire lawyers and obtain standard patents or copyrights on their seeds with the intent of letting just about anyone use them (excluding mammoth private companies, of course). Alternatively, they could try to create a kind of open-source license that allows people to use seeds only if they, too, agree to freely share them and anything they make with them. Goldman has also proposed a compromise in which breeders license some seeds to the private sector to make a profit but give others away.

Klee wonders whether a certain degree of conciliation is the best way forward. "The reality is that we in academia cannot compete with the Monsantos or other big seed companies," he says. "Breeders at universities are pushed out of big crops and into niche crops. In my department, we have a peach breeder, a blueberry breeder and a strawberry breeder. I know a lot of people at Monsanto who have dropped these kinds of crops that are marginal for them." Such dichotomy, he hopes, can be complementary, with the public and private sector relying on each other for distinct specialties.

Ultimately what Klee cares most about is the same prospect tantalizing more and more plant breeders: bridging the gulf between what growers need to make a living and what consumers want on their plates. "Marker-assisted breeding makes it possible to go back and fix things like flavor and texture," Klee says. "In the end, it's really very simple: let's give people stuff they like." SA

Ferris Jabr is a contributing writer at *Scientific American* and a freelance journalist. He has written for the *New York Times Magazine*, *Wired*, *Aeon* and *Nautilus*.

MORE TO EXPLORE

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FOOD FOR TOMORROW

THE GREENHOUSE HAMBURGER

Producing beef for the table has a surprising environmental cost: it releases prodigious amounts of heat-trapping greenhouse gases

By Nathan Fiala

MOST OF US ARE AWARE that our cars, our coal- or gas-generated electric power and even our cement factories adversely affect the environment. Until recently, however, the foods we eat had gotten a pass in the discussion. Yet according to a 2013 report by the United Nations Food and Agriculture Organization (FAO), the livestock supply chain that produces meat and milk for our diets causes more greenhouse gases—carbon dioxide (CO_2), methane, nitrous oxide and the like—to spew into the atmosphere than does either transportation or industry. (Greenhouse gases trap solar energy, thereby warming the earth's surface. Because gases vary in greenhouse potency, scientists tally them according to the amount of CO_2 that would have the same warming effect over decades.)

The FAO report found that livestock production contributes 7.1 billion tons of "CO_2-equivalent" greenhouse gases, which amounts to 14.5 percent of the global emissions of these gases. Producing a half-pound hamburger—a patty of meat the size of two decks of cards—releases as much greenhouse gas into the atmosphere as driving a typical passenger vehicle for 37 miles.

In truth, every food we consume, vegetables and fruits included, incurs hidden environmental costs: transportation, refrigeration and fuel for farming, as well as methane emissions from plants and animals, all lead to a buildup of atmospheric greenhouse gases. Take asparagus: in a report prepared for the city of Seattle, Daniel J. Morgan, now at Vanderbilt University, and his co-workers found that growing just half a pound of the vegetable in Peru emits greenhouse gases equivalent to 1.2 ounces of CO_2—as a result of applying insecticide and fertilizer, pumping water and running heavy, gas-guzzling farm equipment. To refrigerate and transport the vegetable to an American dinner table generates another two ounces of CO_2-equivalent greenhouse gases, for a total CO_2 equivalent of 3.2 ounces.

That is nothing compared to beef. The 2013 FAO study estimated that, while the details depend on the production method, specialized beef cattle emit on average 1.25 pounds of methane for each pound of beef they produce. Because methane has roughly 23 times the global-warming potential of CO_2, those emissions are the equivalent of releasing roughly 29 pounds of CO_2 into the atmosphere for each pound of beef produced.

Raising animals also requires a large amount of feed or grazing land per unit of body weight. Changes in land cover from forest or meadow to pasture exact a carbon price, as does nitrous oxide emitted by fertilizer and feed crop residues.

IN BRIEF

Pound for pound, beef production generates greenhouse gases that contribute nearly 13 times as much to global warming as do the gases emitted from producing chicken. For potatoes, the multiplier is more than 350.

Beef consumption is rising rapidly, both as population increases and as people eat more meat.

Producing the annual beef diet of the average American emits as much greenhouse gas as a car driven 1,300 miles.

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ANDY POTTS

These sources add another 22.2 pounds of CO_2-equivalent greenhouse gases for every pound of food obtained from the cattle. Finally, farms for raising animals produce copious manure and other wastes that give rise to greenhouse gases.

Taking such factors into account, the FAO figured that in beef production, each pound of carcass weight generates the equivalent of 67.6 pounds of CO_2—pound for pound, more than 300 times the amount emitted by producing asparagus.

That number lumps the less desirable parts of the carcass—used for bone meal and dog food—along with the high-quality meat, and it reflects a global average. The emissions intensity is higher still for beef meat, and it varies widely across the world. In the least efficient operations, a pound of protein from beef may come at the cost of 500 pounds of CO_2-equivalent emissions. A feedlot, or concentrated animal feeding operation (CAFO), is not only cheaper to run but also has a far lower environmental cost. Yet even the best of these operations still generate the equivalent of 100-plus pounds of CO_2 for every pound of beef protein.

Other common meats have much lower impact on the atmosphere; the FAO estimate that the average per-pound environmental cost of pork protein is about 50 pounds of CO_2-equivalent greenhouse gases, and for chicken protein that cost is about 20 percent lower still.

SOLUTIONS?

WHAT CAN BE DONE? Improving waste management and farming practices would certainly reduce the carbon footprint of beef production. Methane-capturing systems can, in principle, turn the gas into electricity. But those systems remain too costly to be commercially viable.

The dietary choices we make as individuals can also make a difference. Eating locally produced food, for instance, can reduce shipping—although trucking food in small batches from nearby farms saves surprisingly little in greenhouse emissions. The most effective change, for people in the U.S. and the rest of the rich world, would be simply to eat less beef.

The graphics on the following pages quantify the links between beef production and greenhouse gases in sobering detail. The take-home lesson is clear: we ought to give careful thought to diet and its consequences for the planet if we are serious about limiting the emissions of greenhouse gases. SA

Nathan Fiala is an assistant professor in the department of agricultural and resource economics at the University of Connecticut. His work focuses on food security and economic development in Africa and Asia. His study of the environmental impact of consumption, on which this article is based, was published in the journal *Ecological Economics*.

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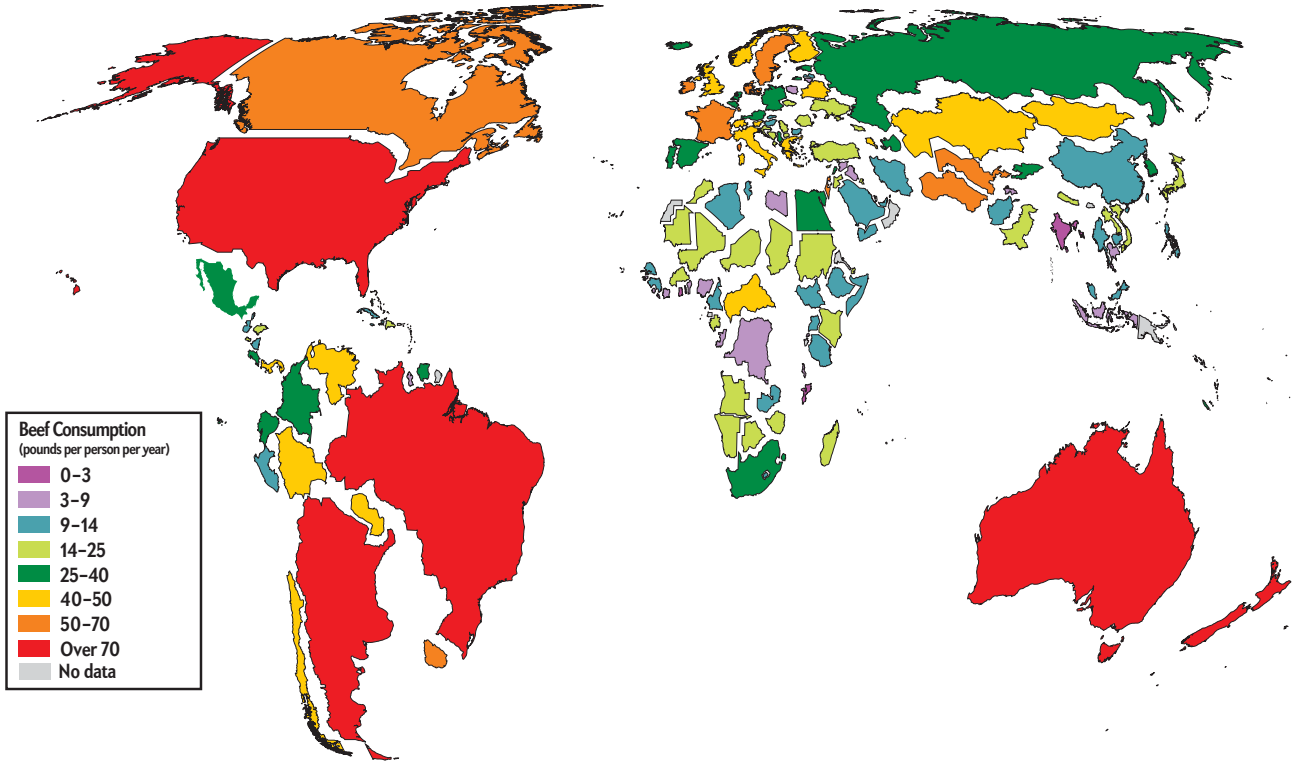
Burgers or Tofu?

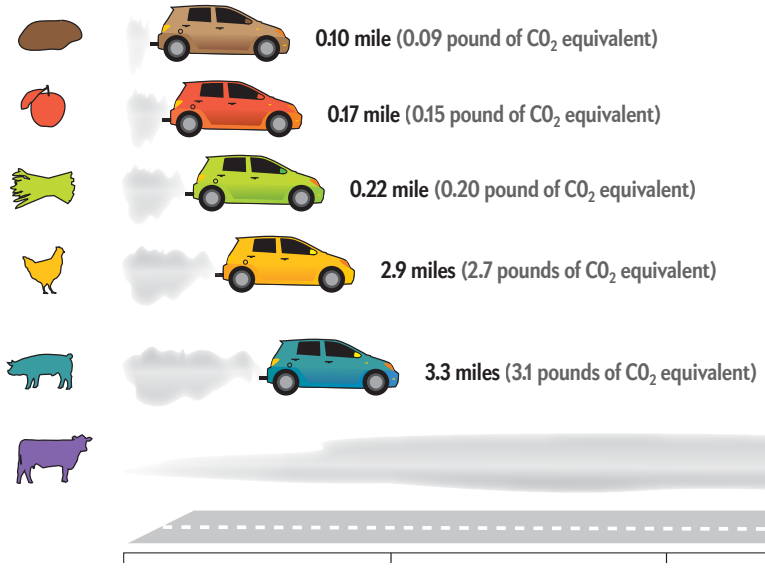
Annual beef consumption, estimated by looking at the annual beef supply per capita (*colors below*), varied in 2011 from 121 pounds in Argentina and 82 pounds in the U.S. to less than two pounds in Liberia and North Korea. The shape of each country in the map is distorted to reflect how much beef consumption per capita there varies from the world median, which is just under 18 pounds per person per year. World beef consumption per capita is growing, particularly in Asia, because of economic development: as people earn higher incomes, they purchase foods they find more desirable.

SOURCE: U.N. FAO



Eating and Driving: An Atmospheric Comparison

Greenhouse Gas Emissions per Half Pound of Food Grown (represented as comparable number of miles driven and pounds of CO_2 equivalent)


0.10 mile (0.09 pound of CO2 equivalent)
0.17 mile (0.15 pound of CO2 equivalent)
0.22 mile (0.20 pound of CO2 equivalent)
2.9 miles (2.7 pounds of CO2 equivalent)
3.3 miles (3.1 pounds of CO2 equivalent)

The greenhouse gas emissions from producing various foods can be appreciated by comparing them with the emissions from a gasoline-powered passenger vehicle car that gets 21.47 miles per gallon (the average mileage of the U.S. car and light-truck fleet in 2011). Greenhouse gases—carbon dioxide (CO_2), methane and nitrous oxide, for instance—trap solar energy and warm the earth's surface. Quantities of greenhouse gases are often expressed as the amount of CO_2 that would have the same global-warming potential: their CO_2 equivalent.

The emissions estimates given here for potatoes, apples and asparagus are for produce sold in Seattle; emissions will vary somewhat for other locations.

SOURCES: U.S. ENVIRONMENTAL PROTECTION AGENCY; "SEATTLE FOOD SYSTEM ENHANCEMENT PROJECT: GREENHOUSE GAS EMISSIONS STUDY," UNIVERSITY OF WASHINGTON, 2007; "TACKLING CLIMATE CHANGE THROUGH LIVESTOCK," BY P. J. GERBER ET AL., U.N. FAO, 2013

MAPPING SPECIALISTS (*map*); LUCY READING-IKKANDA (*illustrations*)

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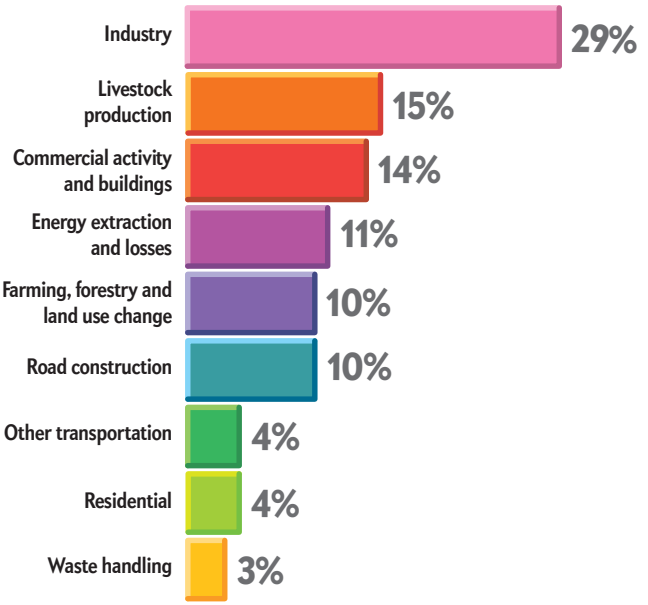
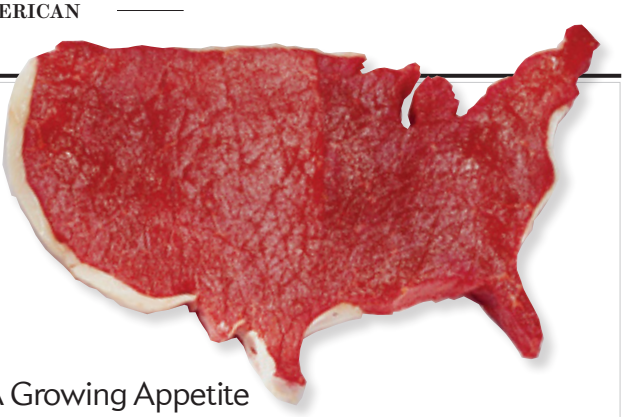
The High (Greenhouse Gas) Cost of Meat

Worldwide meat production (beef, chicken, pork and other livestock) emits more atmospheric greenhouse gases than do all forms of global transportation or commercial activity. A 2013 analysis by the United Nations Food and Agriculture Organization (FAO) estimates that meat production adds 7.1 billion tons of CO_2-equivalent greenhouse gases every year to the atmosphere: some 15 percent of the worldwide annual production of 49.5 billion tons. Only industrial operations generate more greenhouse gases than does raising livestock for food.

SOURCES: U.N. FAO, IPCC





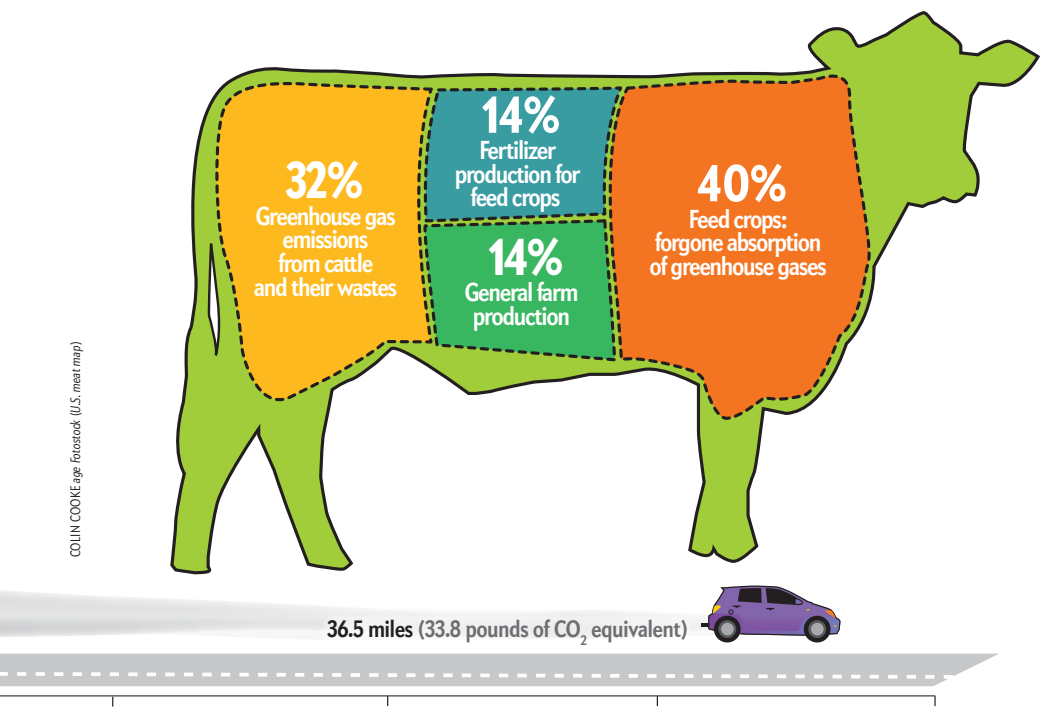
A Growing Appetite

	U.S. Beef Consumption (millions of tons)	CO_2-Equivalent Greenhouse Gases from U.S. Beef Production (millions of tons)	World Beef Consumption (millions of tons)	CO_2-Equivalent Greenhouse Gases from World Beef Production (millions of tons)
2013 (estimated)	13	190	76	1,100
2020 (projected)	12	180	83	1,200
2030 (projected)	14	200	94	1,400
Cumulative	225	3,300	1,500	23,000

QUANTITIES ARE ROUNDED TO TWO SIGNIFICANT DIGITS

World beef production is increasing at a rate of about 1.3 percent a year, in part because of population growth but also because of greater per capita demand in many countries. Economic analysis shows that if all beef were produced under the economically efficient feedlot, or CAFO (concentrated animal feeding operation), system—which generates fewer greenhouse emissions than many other husbandry systems do—beef production by 2030 would still release 1.4 billion tons of CO_2-equivalent greenhouse gases. If current projections of beef consumption are correct, even under the feedlot production system the buildup of CO_2-equivalent greenhouse gases could amount to more than 22 billion tons from 2013 through 2030.

SOURCES: U.N. FAO; U.S. DEPARTMENT OF AGRICULTURE; FIALA, 2008



COLIN COOKE age fotostock (U.S. meat map)

Prime Cuts: How Beef Production Leads to Greenhouse Gases

The largest fraction of the greenhouse effect from beef production comes from the loss of CO_2-absorbing trees, grasses and other year-round plant cover on land where the feed crops are grown and harvested. Second most important is the methane given off by animal waste and by the animals themselves as they digest their food. This analysis of the U.S. feedlot beef-production system was done by ecological economist Susan Subak, while at the University of East Anglia in England.

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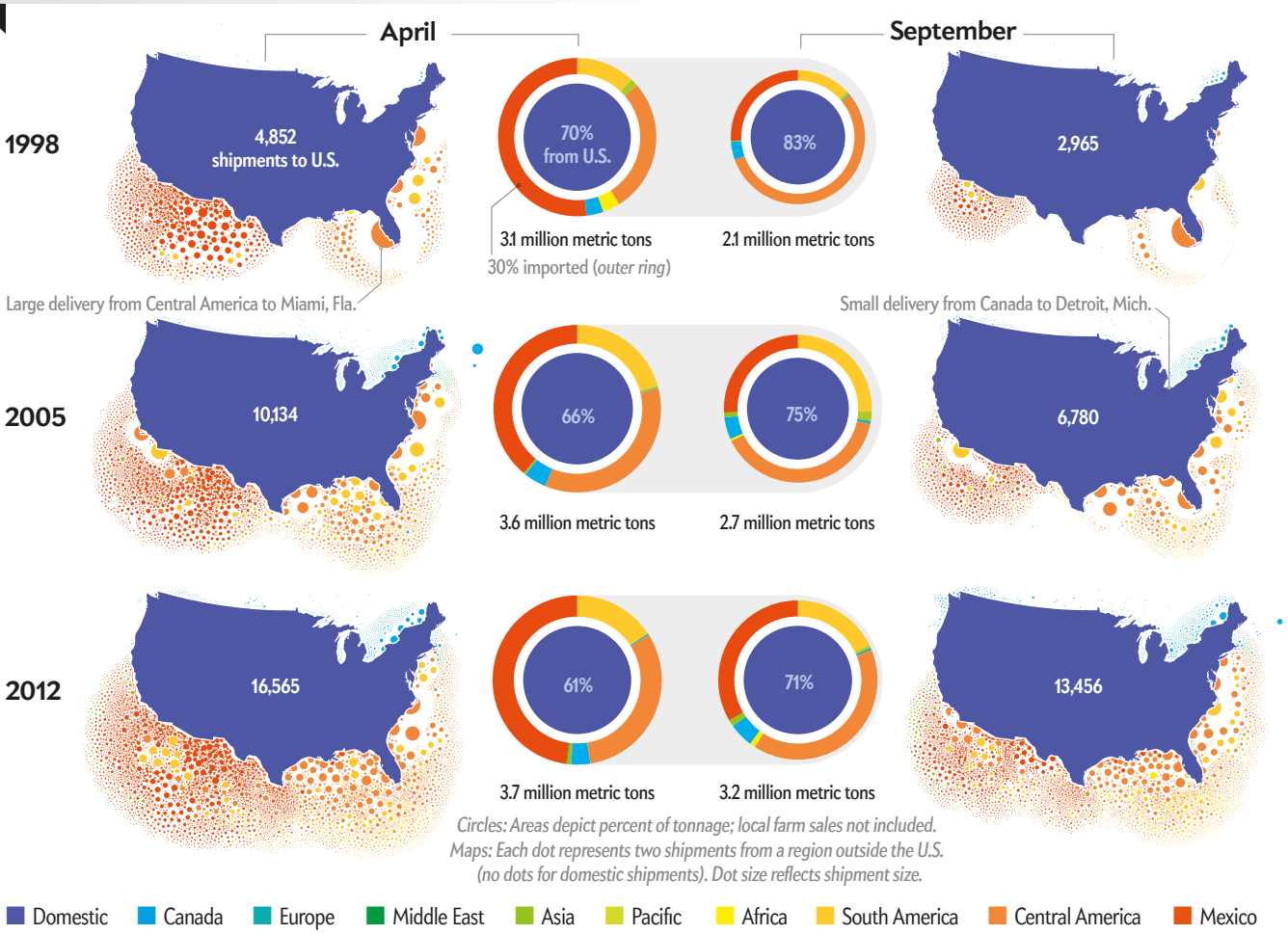
Fruits and Vegetables Shipped to U.S. Distribution Centers



The 5,000-Mile Salad

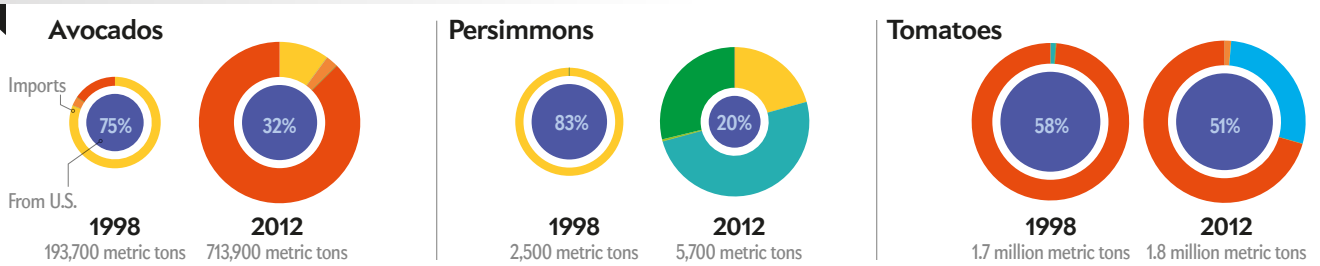
Lettuce from Spain, avocados from Mexico, pomegranates from Israel—all arrive for your dining pleasure

Americans want fresh fruits and vegetables—year-round, not just at harvest time. U.S. farmers grow a lot of produce, but imports are meeting most of the increased demand, especially during off-season months such as April, thus capturing more of the total consumption (*six circles above*).

Mexico, Central America and South America send the most produce to regional distribution centers in the U.S. (*maps above*). Some fruits and vegetables have recently become very popular, whereas others have remained stable (*circles below*). Avocados are way up, persimmons are on the rise and tomatoes are, well, tomatoes.

—Mark Fischetti

As Tastes Evolve, Global Suppliers Respond Annual shipments to U.S. distribution centers



SOURCE: U.S. DEPARTMENT OF AGRICULTURE'S AGRICULTURAL MARKETING SERVICE

Graphic by The Office for Creative Research

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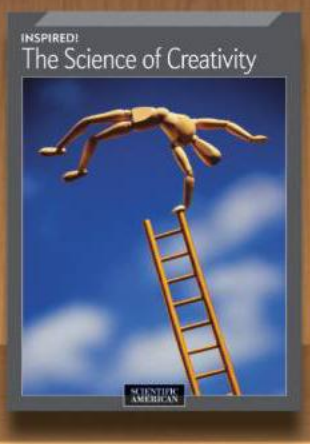
PROMOTION



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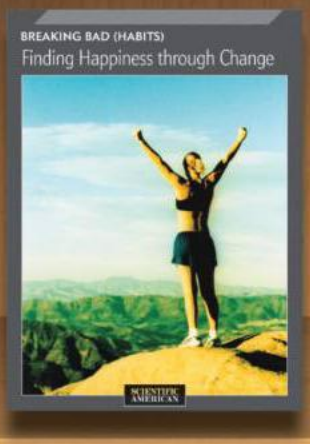

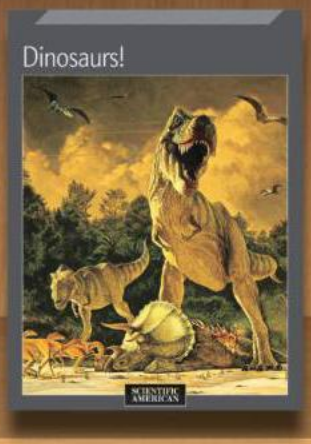

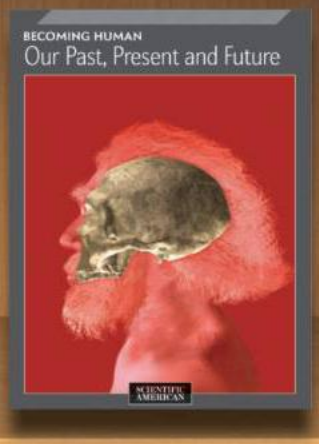

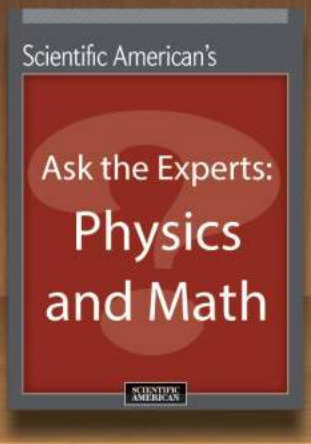

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